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Chip Management in Milling and Drilling of Ductile Cast Iron

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Abstract

This paper presents a comprehensive cross-functional analysis of machining operations for ductile cast iron components in the automotive industry, focusing on the problem of chip carryover and its impact on downstream processes. The research aims to understand the role of machining and identify the source of the issue, by analyzing different machining sequences and the chips that affect the final product or subsequent production stages. To achieve this, the study initially focuses on a 5-axis machining production cell, evaluating the current choice of tooling systems and peripheral processes such as cooling, lubrication, and chip removal solutions. Based on empirical findings, the study presents newly developed solutions to address and minimize the problem of chip carryover in the current production context. These solutions include implementing new sequences of operations and optimizing peripheral processes to prevent chip buildup and reduce the need for manual intervention. The results of the study demonstrate the effectiveness of the proposed solutions in reducing production costs and improving product quality. Overall, this research highlights the importance of a broad and cross-functional approach for developing and implementing improved production strategies. By providing an alternative to a costly manufacturing issue, this study contributes to the ongoing efforts to improve the efficiency and sustainability of manufacturing processes in the automotive industry.

Acronyms

ACEA The European Automobile Manufacturers' Association

BEV Battery Electric Vehicle

CAF Compressed Air Fixture

CAM Computer Aided Machining

DOO Duration of Operation

EDC Electro-Deposition Coating

FEM Finite Element Method

HPCF High Pressure Cutting Fluid

HSS High Speed Steel

ICEV Internal Combustion Engine Vehicle

NC Numerical Control

SMED Single-Minute Exchange of Die

TBL Triple Bottom Line

Nomenclature

α	Clearance angle	$[°]$
α_{WP}	Exit surface slope angle	$[°]$
δ_{max}	Critical elongation	$[\%]$
η	Viscosity	$[N/m^2 \cdot s]$
γ	Rake angle	$[°]$
γ_n	Chamfer angle	$[°]$
κ	Major cutting angle	$[°]$
λ	Thermal conductivity	$[W/mK]$
σ_y	Yield strength	$[MPa]$
σ_{max}	Tensile strength	$[MPa]$
ε	Nose angle	$[°]$
ε_{III}	Strain hardening depth	$[mm]$
a	Radius of contact area	$[mm]$
a_f	Annuity factor	$[\cdot]$
a_p	Depth of cut	$[mm]$
d_1	Initial film thickness	$[mm]$
d_2	Generic film thickness	$[mm]$
E	Modulus of elasticity / Young's modulus	$[GPa]$
f	Feed rate	$[mm/rev]$
f_z	Feed rate per cutting edge	$[mm/rev]$
$F_{adhesion}$	Adhesion force	$[N]$
f_{nom}	Nominal feed rate	$[mm/min]$
h_1	Theoretical chip thickness	$[mm]$
h_{1min}	Minimum Theoretical chip thickness	$[mm]$
HV	Vickers hardness	$[\cdot]$
K	Annual manufacturing cost per cell	$[SEK/year]$
k	Part cost	$[SEK/part]$
K_0	Initial investment	$[SEK]$
k_A	Tool cost	$[SEK]$
k_B	Cost of workpiece material	$[SEK]$
k_{CP}	Operational machine cost	$[SEK/h]$
k_{CS}	Equipment cost during downtime	$[SEK/h]$

k_D	Cost of Personnel	$[SEK/h]$
M	Profit margin per part	$[SEK/part]$
n	Investment lifespan	$[years]$
N_0	Nominal batch size	$[\cdot]$
n_{pA}	Tool life	$[parts/tool]$
p	Interest rate	$[\cdot]$
Q	Annual production capacity	$[parts/year]$
q_P	Production rate	$[\cdot]$
q_Q	Quality exchange	$[\cdot]$
q_S	Downtime ratio	$[\cdot]$
r_β	Edge radius	$[mm]$
r_ε	Nose radius	$[mm]$
R_m	Fracture toughness	$[MPa]$
T	Temperature	$[K]$
t	Time	$[s]$
t_0	Cycle time	$[min]$
T_P	Total production time per batch	$[min]$
T_{su}	Average set-up time	$[min]$
U_{RP}	Production capacity utilization rate	$[\cdot]$
V_c	Cutting velocity	$[m/s]$

Contents

1 Introduction

This section introduces the phenomenon, its background and implications, along with the limits encountered throughout the study. The technical aspects on which this research is based are further explained in the Theoretical Background (section 2), while empirical findings are recorded in section 3. Sections 4 and 5 provide an in depth analysis of the problem at hand. Finally, sections 6 and 7 address all potential improvements that were formulated during this project, as well as practical testing and discussion about their effect on the current production context, respectively.

1.1 Background

The constantly growing and mutating market demand as well as an increasing awareness for unraveling environmental threats, have illuminated the need for more resource efficient manufacturing methods. When it comes to the production of metallic products, machining has long been one of the main contributors to manufacturing because of its effectiveness which, according to Ståhl and Seco Tools (2012) has proven to be of increasing relevance in today´s market. Historically, modern machining originated and was developed in what is known as *conventional turning*; this relatively simplified operation is where the comprehension of the cutting phenomenon and interaction with the workpiece could be developed. The continuous development and increasing complexity in the design of components has eventually outdone the manufacturing possibilities offered by turning in a conventional lathe or milling in a metal shaper. Therefore, nowadays multi-axial milling centers are responsible for producing the largest share of manufactured metallic components. Contrary to other manufacturing methods such as casting, forging, or bending, machining processes rely on material asportation; therefore, managing the removed material is one of the challenges that need to be addressed. In conventional turning chip evacuation occurs for the most part naturally, and by effect of the motion of the workpiece. Conversely, during milling operations, chip management tends to be more difficult since it generally features a semi-stationary workpiece.

Despite recent efforts to transition towards more sustainable means (particularly for what concerns the transportation of goods), the automotive industry has been seeing a rapid growth on multiple fronts. For example, the implementations of the latest technologies and the development of novel materials. From a manufacturing point of view, while new high performance materials will appear in light weight applications, for instance, iron based alloys will still play a significant role also thanks to their desirable recycling efficiency (Harvey 2021). Figure 1.1 presents the general material composition of internal combustion engine vehicles (ICEV) and battery electric vehicles (BEV) respectively (ACEA 2022). While the transition to BEV will redefine the choice of materials to a great extent, steel and casted alloys will continue to occupy the major share. Cast irons remain a valuable option and offer a good variety of properties, currently unmatched by other materials. For example, cast iron alloys can be tailored to be less prone to vibrate, or possess superior wear resistance which makes it a suitable material for some of the critical components in a vehicle (Milosan 2014; Orłowicz et al. 2015).

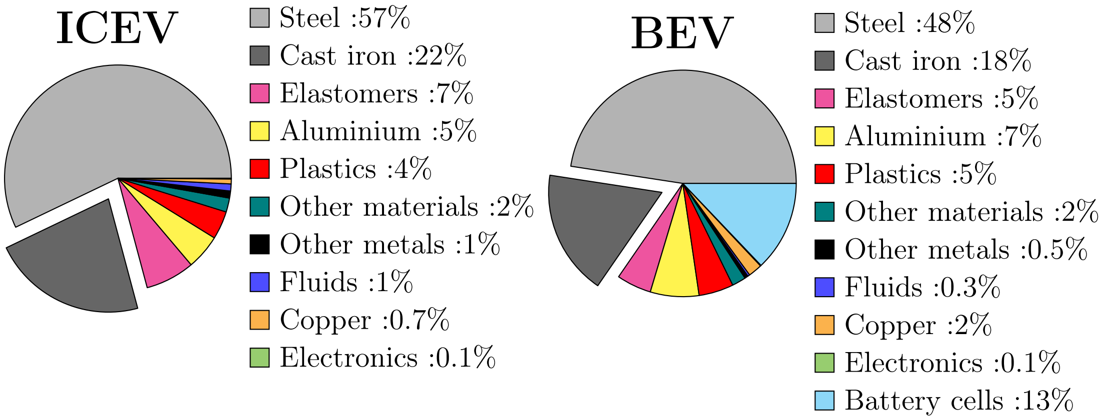


Figure 1.1: Share of materials (by mass percentage) utilized in the production of trucks; adaptation of ACEA (2022).

According to the European Automobile Manufacturers' Association (ACEA 2022), in Europe 77% of freight is transported via roadways on trucks*, all of which require advanced braking systems to comply with new as well as established transport regulations. Moreover, European vehicle manufacturers are producing trucks at a pace of approximately half a million units per year, and are responsible for 52% of the American truck market. At this rate, the European market for transport is sought to gradually gain relevance at a global level over the years to come; therefore, steadily increasing the need for parts and raw materials. As they constitute by far the larger share of functional elements in a vehicle, metallic components will be needed now more than ever, to support this rapid development. With machining operations coming into play, so will peripheral aspects such as chip and burr management. Although this might seem trivial, correct chip and burr management can be a critical part of the functionality of the product and prevention of injuries. For instance, a major cause of engine malfunctions can be attributed to detachment of chips and burrs during normal operation, and should without any doubt, be avoided. Cleaning and de-burring operations have been reported to constitute a share between 8% and 20% of the total cost in manufacturing of complex components in the German automotive industry (Aurich et al. 2009). Furthermore, machining operations will also be playing a key role as almost all components will need to be machined, directly or indirectly (For example, plastic components are often injected in metal moulds that have been machined), at some stage in their production process. Despite changes towards a different type of sustainable economy, and perhaps especially because of this transition, in the coming years a century old operation such as machining, will continue to have a major role in the manufacturing industry. In this field, successful enterprises will be those who have been able to continuously develop their technology by actively taking part in research, and adapt to the resource efficiency and circular economy principles that a changing world requires.

*According to the European Commission (Eurostat 2016), trucks are defined as *"motor vehicles with at least four wheels, used for the carriage of goods"* and are thereby subject to specific regulations.

1.2 Problem Formulation

Milling operations are extensively employed in manufacturing processes due to the process's effectiveness and flexibility in removing material. However, contrary to turning operations, the workpiece is held statically or in a semi-static state (Constrained to a linear feed motion, for example) whereas in turning it would be in constant rotational motion. Therefore, evacuation and removal of metal chips can result more problematic and constitutes a potential source of issues; not only in the machining process but also in downstream and peripheral operations. When the removal of chip in the early stages of production is not effective, and affects later stages in the production flow, the phenomenon can be referred to as *Chip Carryover*.

The aim of this study is henceforth to illuminate the detrimental contributors behind this phenomenon, develop new solutions, and implement successful chip removal strategies. Within this area, contributing factors such as choice of tooling, machine data, product handling, and auxiliary systems, are investigated.

1.3 Limitations

The hereby presented research focuses on a well established production facility for which, over the years, changes and implementations have been added to the original configuration of the production cell and the operating parameters. To provide an answer to the quest that was defined in the problem formulation and at the same time, maintain generalizability in the findings and proposed solutions, aspects such as deviations in individual machine behaviour have not been considered. Nevertheless, in various instances, where changes have been applied to one machine specifically, individual machine behaviour has been considered relevant for a differential analysis. Although not practically relevant from a strict chip carryover point of view, cost parameters were considered when evaluating the implementability of this study and the effect it would have on the current production context. Finally, the major limitation to this project is the allocated time frame in which the evaluation of the newly implemented solutions has been conducted. While empirical findings rely on solid historical data (traced back over nearly 4 years of entries) and 8 months of presence at the site, the implementation and assessment of new solutions is limited by the company's response to change and the time required for it to take place, and the following data acquisition. Although these limits are of non-neglectable relevance, historical data and early trends in later sampling are deemed sufficient to portray a complete and insightful picture of this phenomenon and its future developments.

2 Theoretical Background

In order to provide the reader with a full understanding of the phenomenon and to support the surrounding discussion with relevant and established information, this section presents a summary of the theory pertinent to this topic at the time of investigation.

2.1 Metal Cutting

Metal cutting can be defined as the process of removing the excess material from a metallic *blank* or *workpiece* with the scope of creating features that are functional to the application of the finished product. Such operation is accomplished by the deformation and shear action removal of the base material, in the form of chips, and via the action of a *cutting tool*. Despite the continuous development in the field, the current most recognized models used to describe the metal cutting phenomenon are widely based on the *Single Shear Plane Model* developed by Merchant (1945) and Ernst (1938). A more comprehensive publication by Groover (2020) provides a detailed overview of the topic, inclusive of more recent developments, which could be referenced as the underlying backbone of the theory presented in the following paragraphs.

2.1.1 Tool Geometries

It is well known that the geometry of a cutting tool has a direct effect on the cutting process that impacts it to an even greater extent than cutting data such as feed or depth of cut. There are multiple angles involved in a metal cutting operation, all of which can be altered directly or by selecting a different tool, in order to achieve different cutting results. The influence of the cutting geometry can be observed in the process both from a macro- and micro point of view. Macro-geometry generally entails the major cutting angles of the tool while micro-geometry is a term reserved to describe the cutting edge's angles to a greater level of detail. According to Köhler (2014) while the macro-geometry is defined by the rake angle, other parameters such as clearance angle α, wedge angle, nose radius r_ε and angle of the chamfered edge are all part of the micro-geometry in a cutting tool. The tool may also present an edge radius r_β to relieve the cutting edge of high stress concentration. This figure is generally expressed by the mean or by a significant value, as the effective geometry may be a conical surface or present a variable radius along the length of the cutting edge. Figure 2.1 illustrates the presence of a major rake angle γ and locally, the presence of what Agmell et al. (2017) define as chamfer angle γ_n. This second angle is a localized change of the rake angle which takes part in defining the micro-geometry of the cutting tool and, in this case, it is implemented to further improve the resistance of the cutting edge in intermittent operations or for machining of materials that require this type of geometry (Ståhl and Seco Tools 2012). Another aspect that can be related to the micro-geometry of a tool is the presence of a chip breaking solution on the back of the tool. The description of such feature is addressed in section 2.1.3.

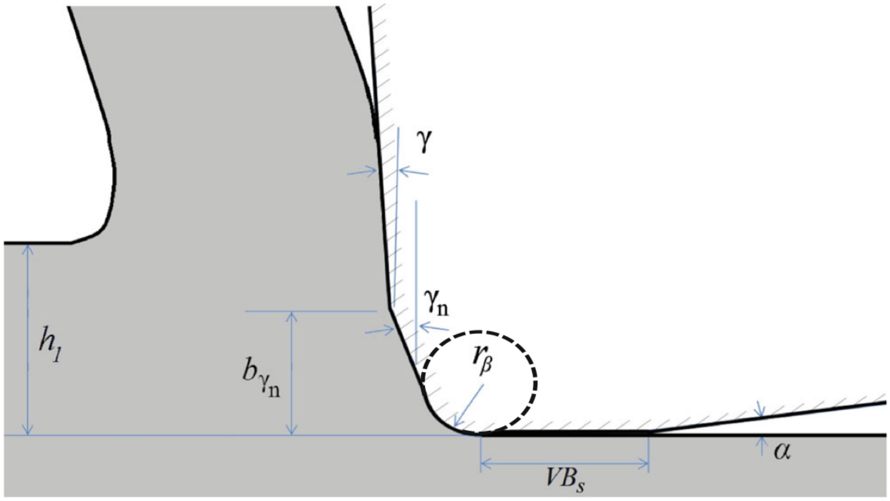


Figure 2.1: Cutting tool geometry and angles (Agmell et al. 2017).

To refresh the reader's knowledge and to provide an overview of the terminology that is utilized in this report, figure 2.2 illustrates the most important cutting angles in milling operations. Some of the principal angles in milling operations are defined in different ways depending if they have an axial and radial reference in relation to the main axis of the milling tool; these peculiarities are elucidated where needed in the text.

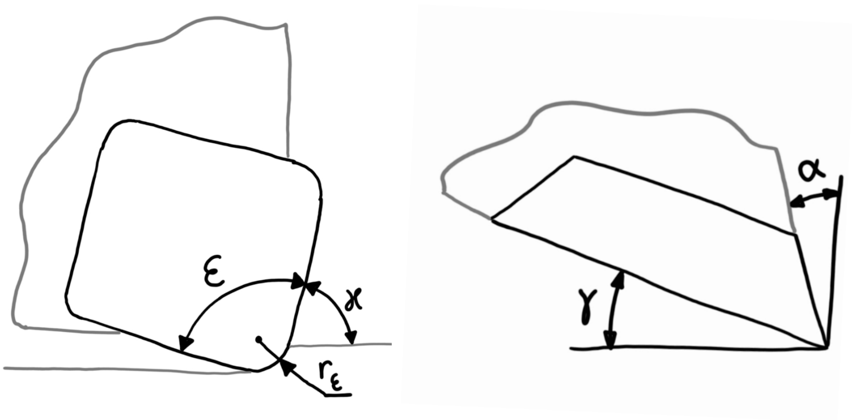


Figure 2.2: Tool geometry and angles in milling operations.

2.1.2 Stagnation Zone

As previously mentioned, the main purpose of the cutting edge is to split the material to be removed by separating the chip from the workpiece with a shearing action. Due to the cinematic equilibrium of the shearing mechanism, there will always be a point on the edge of the tool that identifies the boundary between the base material of the workpiece (which is stationary in a relative coordinate system) and the chip that simultaneously forms and gets evacuated. This point that can be localized on the extremity of the cutting edge, defines the position of the stagnation zone (Ståhl and Seco Tools 2012). The stagnation zone is a line on which shear and deformation occur, and which separates the workpiece with the chips. In other words, relatively to the cutting tool, the stagnation zone can be imagined as the area where cutting occurs and the chips are parted from the workpiece. Outside the boundaries of this zone, material will be flowing to either side of the cutting edge, resulting in compression into the workpiece and the movement/curl of the chip. The small deformation that inevitably results in the outermost layers of the freshly machined surface can cause hardening of the workpiece's surface as better illustrated in section 2.1.3. In a tri-dimensional problem formulation, the line that identifies the stagnation zone defines a planar region. Across this plane, the maximum shear stresses can be found at the stagnation point and will develop while moving out towards the surface of the workpiece. Although it is known that this shear plane ultimately dictates the formation and breaking of the chip, how to practically take advantage of this information to control the position of this plane during continuous machining is still a topic in need of further comprehension (Bil et al. 2004; Toropov and Ko 2007).

Knowledge about the stagnation zone and management of the shear plane is still a relatively novel topic, currently being researched on many fronts in academy. The stagnation point is illustrated in figure 2.3 along with the stagnation zone. The shear plane develops along the stagnation zone on the first planar direction and perpendicularly to this page, on the second one. The color gradient in the image indicates the equivalent stress distribution according to Von Mises' laws, in the workpiece material and tool, and more importantly, peaks in the identification of the shear plane (Light green sloped line on the left side of the cutting tool).

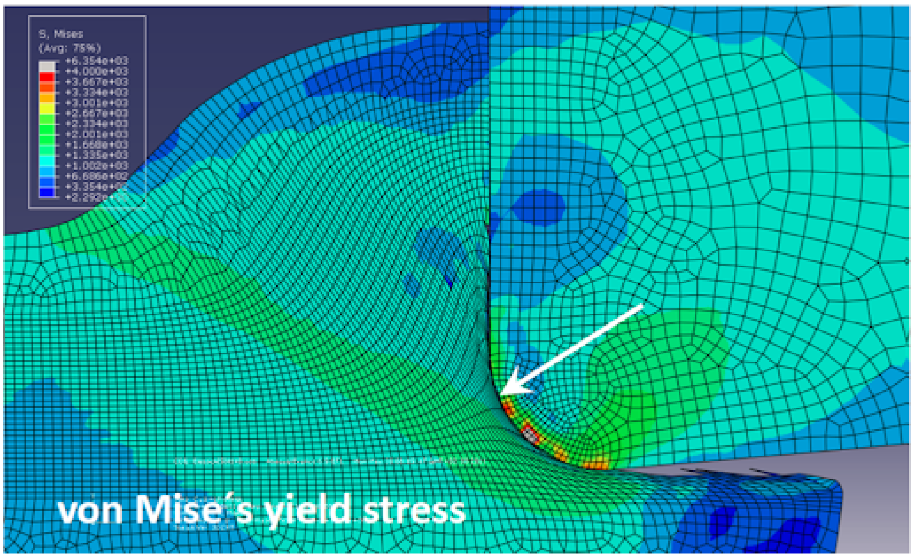


Figure 2.3: Stagnation point (Arrow) and shear plane (On the left side) adapted by Agmell (2011) from Ståhl and Seco Tools (2012).

2.1.3 Chip Formation

In terms of chip management, high-frequency chip breaking is in general desirable. Otherwise, the formation of longer chips may cause issues by potentially creating entanglements that can interfere with the metal cutting operation. Short chips have many other benefits including but not limited to, easier removal from internal geometries and accumulation points in the workpiece; whereas longer or larger chips might get stuck in a more permanent manner. In longitudinal metal cutting a general relation between the depth of cut and the feed rate or theoretical chip thickness can be evaluated in terms of its machinability from a chip formation perspective. This behavior essentially follows the model illustrated by figure 2.4 inspired by the results of Ståhl et al. (2024), where the curve highlights a region of combined cutting parameters favourable for effective machinability conditions. Despite the proven validity of this model, it has been experienced that the chip formation is a product of multiple factors related to tooling, workpiece, machine data, and cutting fluid. Therefore, while this model provides reliable information, its implementation should not ignore the presence of additional contributing factors. For example, by the interaction of tool geometry and material specifications, chip breaking features, cutting conditions, workpiece material properties, cutting fluid and process variation (Jawahir 1988).

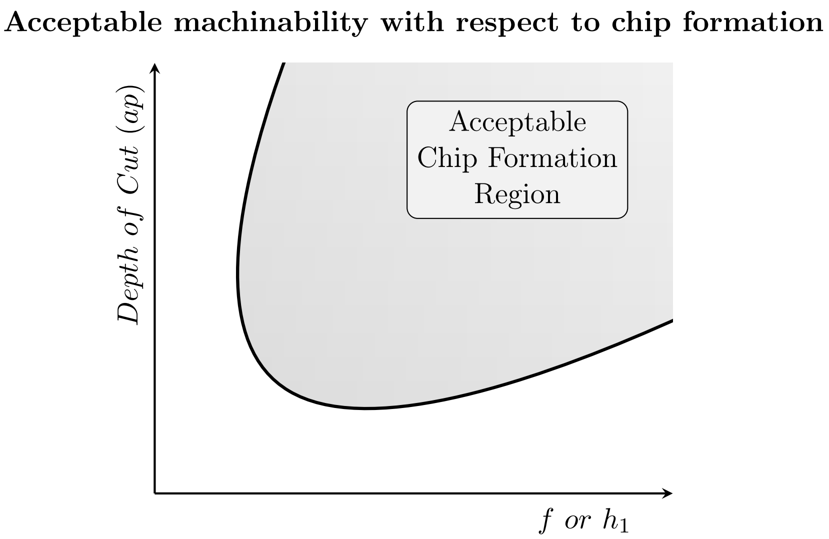


Figure 2.4: Machinability with regards to chip formation as function of feed and depth of cut, modified after Ståhl et al. (2024).

When a chip is formed by the action of a cutting tool, it can undertake a second deformation in addition to the one connected with the chip removal processes itself. This phenomenon is referred to as *chip curling* and it can be divided into two main categories; free and forced curling. Essentially, *free* implies that curling naturally occurs after losing contact with the cutting edge or external obstacles. Conversely, chip curling can be *forced* by the interaction with an external obstacle such as a chip breaker geometry, which can be integrated in the design of the cutting tool or added to it (Lotfi et al. 2015). Such features are nowadays commonly part of most insert designs as correctly managing the formation and breakage of the chip has become of relevant importance, especially when production is conducted in unsupervised and automated machines, where failure could cause significant standstills. Additionally, the manufacturing methods for sintered inserts allow for easy and cost effective implementation of such features. Chip breaking due to curling is closely linked to the bending stresses resulting within the chip, whose opposite sides are subjected to tension and compression respectively (Chungchoo and Saini 2002; Lotfi et al. 2015).

Consequently, material properties such as modulus of elasticity, ductility and strength of the workpiece material are factors that influence the chip formation behavior (Chungchoo and Saini 2002; Lotfi et al. 2015; Yılmaz et al. 2020). In general operations, the resulting short chips are to be considered a positive outcome and are more easily evacuated from the workpiece either by the action of pressurized cutting fluid or by the movement of the machine. On the other side, long chips are generally disliked because of the increased risk of chips interfering with the machining operation or if they remain captured in the workpiece, potentially causing problems later on in the manufacturing process. The main idea behind chip breaking micro-geometries is to force the curling of the chip until the radius of the curl results in the discrepancy of the compressive and tensile stresses on the two sides to be large enough to cause breakage. This phenomenon is graphically illustrated in figure 2.5 where the chip breaking feature is applied to the shank of the cutting tool (Left) rather than a built-in solution which can be observed in modern sintered inserts (Right).

Other methods of forcing chip breakage include, but are not limited to, the effect of cutting data, coolant and/or cutting fluid; however, research shows that for cast irons chip breaking geometries are most commonly employed (Yılmaz et al. 2020). Chip formation plays an especially relevant factor in drilling operations or in any other instance where the geometry of the workpiece is prone to accommodate and trap the resulting chips. In this cases especially, the shape and size of the chip dictates how chips are expelled, or not, from the workpiece. Failing in chip removal can cause drills to clog, hence resulting in higher forces, lower tool life, and worse surface finish, as well as potentially causing immediate tool failure with the consequent risk of having to discard the workpiece. Drilling of holes is most commonly performed with solid high speed steel (HSS) or sintered twist drills that rely on the "cork" action of the helix angle naturally embedded in their design, to discharge chips from the cutting edge to the external environment. In such applications, the formation of large spiraled chips can be more impervious to effective removal as opposed to short chips or thinner shavings. Less obstructive chip formations can be obtained by utilizing *chip splitting nicks* on the cutting edge of solid drills. Such details can be considered as micro geometries and provide many benefits including lower cutting forces, extended tool life, and reduced burr formations on the exit surface of through holes (Ogawa and Nakayama 1985). For holes machined by the action of drilling tools with removable inserts, otherwise known as *short-drills*, the chip formation is more closely related to what previously described for milling operations in general.

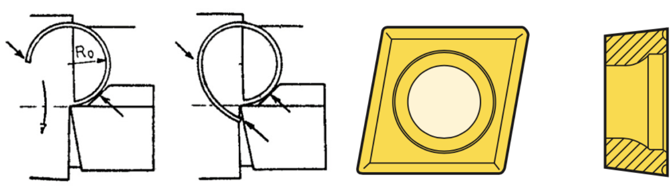


Figure 2.5: Forced chip curling and chip breaker (Nakayama 1962) (left) and insert with built in chip breaking feature (Seco Tools 2021) (Right).

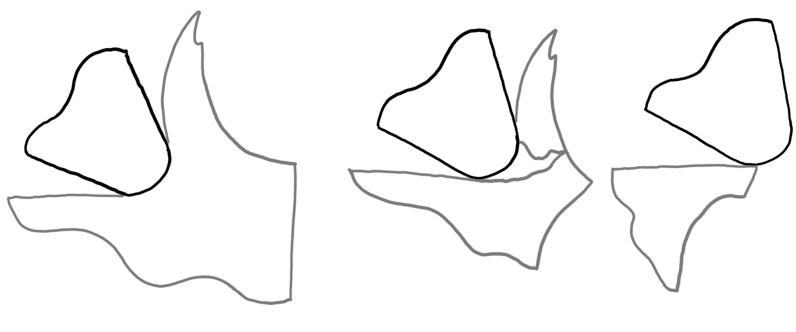
Another contributing factor in the chip formation process is the theoretical chip thickness h_1 and its minimum value h_{1min} for which the machining operation still proceeds as a regular cutting process (Ståhl and Seco Tools 2012). As h_1 approaches h_{1min}, the material will instead have the tendency to deform and strain harden into the workpiece (Manjunathaiah and Endres 2000). Lower values for h_1 also imply that less material is removed per revolution of the cutting tool. When the chip thickness is such that the cutting process is disrupted and deformation occurs, the material encounters a deformation induced strain hardening process which may affect the workpiece to a given depth ε_{III} (Ståhl and Seco Tools 2012). This phenomenon is especially true when $h_1 \leq h_{1min}$, but strain hardening is always present to a certain extent, even when machining occurs at a conventional regime. The effects become more evident and problematic at smaller values of h_1, and for tools with larger edge radii r_β (Manjunathaiah and Endres 2000).

The consequence of a strain hardened layer on machining operations is that the tool will encounter material with greater hardness which in turn may result in increased cutting resistance and tool wear compared to the undeformed workpiece material. When a machining operation is performed in multiple passes, each pass contributes to creating a thicker and/or harder layer (Ståhl and Seco Tools 2012). In other words, when the chip thickness is sufficiently low (h_1 approaching h_{1min}) and the deformed layer is not removed via a cutting operation, the following passes will cause the strain hardened layer to propagate by effect of the same deformation phenomenon. Therefore, as h_1 decreases (and for larger r_β) the depth to which strain hardening occurs will increase and, when h_1 is sufficiently small, the hardened layer may become greater than the theoretical chip thickness itself (Manjunathaiah and Endres 2000; Ståhl and Seco Tools 2012). When the deformed region exceeds the chip thickness h_1 of the following machining passes ($|\varepsilon_{III} - h_1|$) the hardened zone will continue to persist. For sufficiently low h_1 the material being processed may have strain hardened over multiple previous passes (Ståhl and Seco Tools 2012). This phenomenon can be avoided by defining an optimal chip thickness either experimentally or by relying on further theory which at this time might not be sufficiently developed to be easily applied in an industrial scenario. The cutting resistance is a function of the chip thickness as established by Groover (2020); however, chip thickness is also bound to the formation of a deformed layer in which strain hardening occurs. As previously mentioned, this deformed layer will in turn cause the cutting resistance to increase, for lower values of $h1$, as strain hardening becomes more prominent. The implicit formulation of this phenomenon makes it difficult to analytically pre-determine an optimal value for $h1$, which by logic should fall between h_{1min} and ε_{III} ($h_{1min} < h_1 < \varepsilon_{III}$). Higher chip thickness will normally cause the cutting resistance to increase, while lower values, after an initial decrease in cutting resistance will see a sudden increase as h_{1min} is approached.

In drilling operations, where the presence of tool exit burrs is common, higher degrees of strain hardening may facilitate the formation of drill caps/burrs, as the increase in cutting resistance is not matched by an increase in the supporting structure which would prevent such formation, facilitated by the effect of the constant axial (in the feed direction) force.

2.1.4 Burr Formation

When machining intermittently or when exiting the workpiece, it is common for *rollover* burrs to form. Such burrs occur when the cutting edge of the tool, previously engaged in the bulk material, suddenly exits from the workpiece. When this occurs, the material can roll over the edge instead of breaking off in the form of chips. The formation of this type of burrs is a consequence of the reacting forces offering structural support to the adjacent area of the workpiece, being lower than the resulting forces of the cutting operation. Thereby deformation will be caused through displacement of the full material body rather than splitting of the body via a cut motion. An example is illustrated in figure 2.6. With regards to what described about Stagnation Zone in section 2.1.2, particularly in cases when the workpiece does not provide reaction force due to the lack of supporting material, the stagnation point ceases to exist. In practice, the lack of a stagnation point means that there is no separation in the flow of material; instead of cutting the chip away from the workpiece, material is removed in bulk as a burr (Ståhl and Seco Tools 2012). While ductile materials are generally more prone to the formation of rollover burrs that remain connected to the workpiece, in brittle materials the burr formation might break from the workpiece and occasionally damage its edge. Similarly, the formation of burrs can also appear when machining is performed perpendicular to an edge on the workpiece; in this case burrs are traditionally referred to as Poisson burrs (Ståhl and Seco Tools 2012). When the material is characterized by a brittle behaviour, the formation of burrs can result in rather large, occasionally odd shaped, burrs that can be confused for chips. The formation of burrs is not only problematic as it may damage the product but also because it may negatively affect how different parts interact into a common assembly. For manufacturing where handling operations are carried out by humans, the presence of burrs my also cause sharp edges that can be harmful for the operators to handle (Roman 2018).



– cutting direction ⟶

Figure 2.6: Evolution and formation of a rolled over burr.

There are multiple ways to influence the formation of such burrs; Aurich et al. (2009) propose a thorough review of *burr control strategies* including, but not limited to, tooling, coolant and lubrication, and cutting data. A common method to prevent the formation of burrs is to guide the stagnation zone during the exit phase by chamfering the edges of the exit. This phenomenon is also dependant on the choice of material, as different mechanical properties will dictate a different propagation of the stresses throughout the workpiece. However, it is often not possible to implement such changes for products after the early development stages. Therefore, it is not seldom for burr formation to be contrasted by tooling choices, cutting data and process sequencing adaptations. Similarly to altering the geometry of the workpiece, manipulation of the tool geometry can entail less prominent burr formation. Most notably, this can be achieved by adjusting the edge radius (r_β) but also by increasing the clearance angle (α). It is proven that while lower edge radius (r_β) will favour the cutting motion of the tool, higher values of this parameter will augment the formation of larger burrs. In a similar way, an increased clearance angle (α) reduces tendency of burr formation (Ståhl et al. 2024).

In drilling operations, the formation of burr and discs occurs similarly to the general conditions described above, with the notable difference being that the axial direction of the drill will be incident to the exit surface. Tool exit burrs in drilling are often referred to as drill caps, or just disc burrs; and more often than not, they are confused for chips. Additionally, when operating with very ductile materials such as some aluminium alloys, it is not uncommon for holes to present a crown burr around the exit perimeter of the feature. The dynamic of drilling operations implies that the material is removed from the workpiece through a cutting motion until that cutting edge has approached the exit surface to the point at which the supporting structure of the workpiece is weakened. Because of this, once the situation is encountered, the burr formation can be easily pushed and detached from the workpiece as in this weakened state, the energy required by the axial force of the drill to push the burr will be lower than what required by the tangential motion of the cutting edge to perform a cut (Dornfeld et al. 1999). Generally, due to this behaviour, increased feed rate f will result in drilling operations being more prone to experience disc and burr formation (Min et al. 2003). Nevertheless, exit surfaces that present a geometry that is not completely flat and perpendicular to the drilling direction, will have a beneficial influence on the formation and possible detachment of (disc) burrs. In the simplest of cases, a modified exit geometry would consist of a sloped surface. In this case, the cutting edge will break through on the side closest to the drill (shortest path), and in a predictable manner if the feed rate f is comparatively small in relation to the angle of the exit slope. Furthermore, this relation can be described with the use of the nominal feed f_{nom} and cutting velocity V_c and how that relates to the slope of the exit surface α_{WP} as presented in equation 1 (Min et al. 2003). This means, that at a given slope angle, a relation between V_c and f_{nom} can be established. An ideal slope can be designed in the workpiece prior to production once the theoretical cutting data has been established.

$$\alpha_{WP} \geq \arctan \frac{f_{nom}}{V_c} \tag{1}$$

Thereby, a reduction in feed rate likewise increases the predictability of the initial break-through position and hence the behavior of the chip formation. Meaning that lower feed rates and higher inclination angles of the exit surface will provide fewer burrs; this is also supported by (Leitz et al. 2010) who builds onto an earlier model developed by (Min

2001). Figure 2.7 illustrates two exit surfaces with different slope angles. Finally, according to Gillespie (1973), while changing a single parameter will most likely not prevent the formation of burrs by itself, when the cutting process is examined as a whole and the effect of multiple interacting parameters combined, burrs can be minimized significantly.

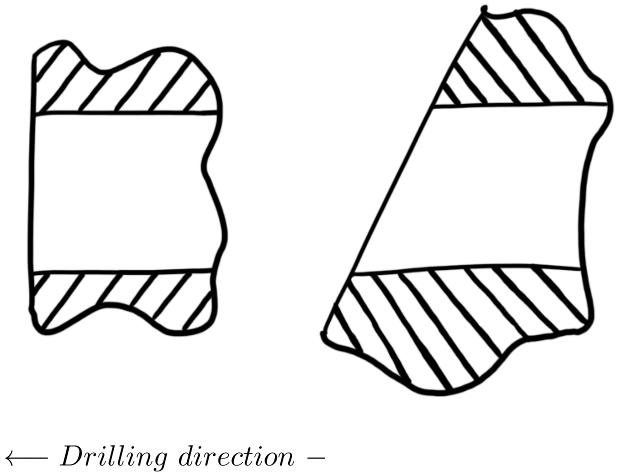


Figure 2.7: Cast design; flat and sloped exit surfaces.

2.2 Chip Asportation

Chip asportation is often an underestimated aspect of manufacturing which is very closely related to chip formation and machine operations, but also has a significant impact on cost and the whole downstream manufacturing processes. Once the chip has been formed by effect of the cutting operation, it can be removed by mean of different factors. For processes where a cooling/lubricating fluid is employed at high capacity, the flow of the liquid can be an effective method in removing the material. In addition, the movements of the machine, in combination with the already mentioned action of the process fluids, can aid this operation. Other methods for asportation include the use of compressed air, or less commonly the implementation of specifically engineered solutions. This necessity is accentuated in extreme operations such as gun-drilling where effective chip removal is instrumental for a positive outcome (Jung and Ni 2003). Some chip types, such as drill caps can be difficult to remove in products featuring various types of cavities because of their particular size and shape (Dornfeld et al. 1999). Although the need for chip removal can seem trivial, the consequences can be costly and often require additional handling in order to effectively clean the parts from the chips.

Chip asportation does not only entail chips but, on a greater scale, can also include burrs and burr removal. Similarly to chips, the removal of burrs is both connected to machine operations and additional operations that happen externally from the machine. Previous research suggests that burr related aspects can constitute approximately 15% increase in both required manpower and cycle times, and it may also result in re-machining of parts (approximately 2%) and potential machine failures (approximately 4%) (Aurich et al. 2009).

2.3 Fluid Interaction

Machining operations generally require the presence of cutting fluids for multiple reasons. The first one is that lubrication is often employed to reduce the cutting forces and tool wear, and the second one being that the flow of a cutting fluid can be employed to cool down both the workpiece and the cutting tool (Yan et al. 2016). Modern cutting fluids are commonly water based oil emulsions (with several additives) and are able to fulfill both functions simultaneously. Additionally, fluids can also be employed for chip removal as previously mentioned. Cutting fluids constitute a significant cost in the manufacturing process, according to Sreejith and Ngoi (2000) cutting fluids can affect the cost up to 20% of the whole machining process; making a conscious, if not minimal use of this products is therefore of increasing interest.

Operational temperature is one of the strongest links to tool wear and while much of the heat is transported away with the removed chips, cutting fluid can be the major cooling source for a given machining process (Ståhl and Seco Tools 2012; Yılmaz et al. 2020). Despite this positive and desired effect, the presence of coolant can cause problems and additional costs, especially if it remains present on the workpiece after machining operations are completed. Cutting fluids are known to be dangerous for the environment and for the operators that might get in contact with it (Hallock et al. 1994).

Besides, in the presence of chips from machining, after the operations are completed, cutting fluids can provide a binding action between the workpiece and chips that is detrimental to the removal of chips from the surface of the workpiece (Shokrani et al. 2012). When two contacting surfaces are separated only by the presence of a thin layer of fluid, the parting of the two will be contrasted by the presence of a fluid-solid adhesion phenomenon. The adhesion is primarily a function of contact area and the adhesive strength of the solvent, as illustrated by Reynolds in equation 2 (Reynolds 1886). Equation 2 expresses the relationship the force $F_{Adhesion}$ required to separate two disc surfaces of radius a, separated by a fluid with viscosity η, from an original distance d_1 to a final distance d_2 over a time interval t (Bikerman 1947). Note that distances d_1 and d_2 correspond to the thickness of the liquid film in between surfaces, reaching a critical film thickness will cause the two surfaces to separate. Due to its very peculiar definition, adhesive force is often expressed in *dynes* (A measurement unit defined as $dynes = \left[g \cdot cm/s^2\right]$, equivalent to 10^{-5} Newton). Furthermore, as experimentally observed by McFarlane and Tabor (1950), the adhesive strength of a fluid is also influenced by elapsed time and temperature of the system. This phenomenon has a linear relationship between the inverse of time (t^{-1}) and adhesion in which the temperature dictates the gradient illustrated in figure 2.8. This implies that there exists a convergence at $\lim_{t\to\infty} 1/t$ for which the liquid reaches its steady-state adhesive strength that is independent of time and temperature. Higher temperatures in line with the illustration in figure 2.8, approach the steady-state strength more rapidly.

$$F_{adhesion} = \frac{3 \cdot \eta \cdot a^2}{t \cdot 4} \cdot \left(\frac{1}{d_1^2} + \frac{1}{d_2^2}\right) \tag{2}$$

In practice, this means that once the initial transient has elapsed and the parts have reached room temperature, all chips are subject to a proportionally equal adhesive strength. This being said, the fluid interaction model hereby presented is an extreme simplification that cannot find a direct application in the experimentation conducted during this research project and therefore, it should only be considered as a theoretical digression.

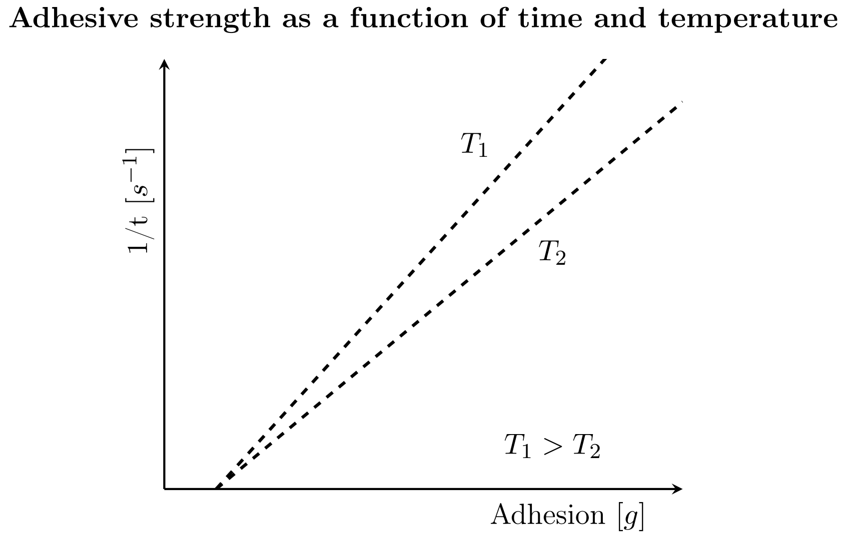


Figure 2.8: Adhesive strength as a function of time and temperature $f(t, T)$; as adapted by McFarlane and Tabor (1950).

Overall, cutting fluids have more benefits than a mere increase in tool life. Additionally to what has already been mentioned, the usage of fluid can be tuned to significantly increase chip breaking frequency by adjusting the operating pressure. How high of a pressure is required, depends on the scenario and cutting data. In general, recent literature suggests it would require a minimum of 20 MPa of cutting fluid pressure to effectively see an improvement in the chip breaking frequency (Yılmaz et al. 2020).

Drilling is slightly different to that of conventional turning and milling since the coolant is enclosed in the hole and henceforth acts to a certain degree as a chip removal medium. Traditionally, coolant is applied at significantly lower pressure than the requirement of 20 MPa highlighted by Yılmaz et al. (2020); typically ranging from 0.17 to 0.55 MPa according to López de Lacalle et al. (2000). Döbbeler and Klocke (2017) conducted a study on chip *breakability* during drilling with various nozzle diameters and pressures of applied cutting fluid. Similarly to turning and milling, an increased pressure and nozzle size increased the tendency of chip breakage. Furthermore, Lindeke et al. (1995) reports of a successful implementation of HPCF which increased tool life by a factor of ten whilst eliminating half the cycle time by transitioning from conventional to high pressure cooling (López de Lacalle et al. 2000).

2.4 Manufacturing Sustainability

Although, manufacturing sustainability in its broad definition is dictated by many factors, it ultimately converges into the concepts of environmental, social, and economical sustainability. This tri-dimensional reality was initially brought to attention by WCED (1987) and only in a second instance developed into what is currently referred by literature as the *triple bottom line* (TBL) (Elkington 2013). The dimension which is most commonly associated with sustainability is the environmental aspect which in recent times, has emerged in an ever tangible concern that calls for prompt and concrete action. Environmental sustainability relates to all manufacturing facets that can be traced back to the usage of resources, future availability, and everything which may have an impact on the natural surroundings. While issues within the industry have now surfaced and concrete actions are taken to protect the environment, it has been proven difficult to holistically establish a metric to assess environmental impact (Delmas and Blass 2010). Nevertheless, it is evident that environmental sustainability can benefit from an increased attention towards manufacturing efficiency (Haldex 2022). Factors such as energy consumption, material usage, ability to be recycled, and in general, use of resources, to mention a few, have a strong impact on sustainability and can be effectively measured with an efficiency index (Angelakoglou and Gaidajis 2015). Social sustainability, on the other hand, introduces a human dimension. In its simplest form, it entails how humans interact with the manufacturing process and methods, how working routines my affect the operators' health, and what role a company plays in the social structure of the local district.

Abbreviation	Description
k_A	Tool cost [SEK]
n_{pA}	Tool life [parts/tool]
k_B	Cost of workpiece material [SEK/Part]
N_0	Batch size [-]
t_0	Cycle time [min]
q_Q	Quality exchange [-]
q_S	Downtime ratio [-]
q_P	Production rate [-]
k_{CP}	Operational machine cost [SEK/h]
k_{CS}	Equipment cost during downtime [SEK/h]
k_D	Cost of personnel [SEK/h]
T_{su}	Average set-up time [min]
U_{RP}	Production capacity utilization [-]
T_P	Total production time per batch [min]
K_{AUH}	Maintenance of tools [SEK]
K_{CUH}	Maintenance of equipment [SEK]
K_{GUH}	Maintenance of material handling equipment [SEK]

Table 2.1: Manufacturing cost model, variables and abbreviations adapted from Ståhl (2011).

Unlike the first two dimensions, economic sustainability is the least abstract out of the TBL and can be easily assessed in monetary terms. This dimension includes many aspects such as a company's ability to be in business for the years to come or the role it may play in the economic development of a country. However, the side that most closely relates to the scope of this project is how a company can sustain the cost of production, in relation to the market value that a product has.

While there are many established cost models that can provide this assessment, Ståhl (2011) presents a detailed formula particularly tailored for the cost evaluation of machining operations which are at the focus of this study. Being able to correctly establish part cost is a crucial aspect that plays a central role in any manufacturing scenario; for this reason, a complete illustration of the original formula and abbreviations are presented in equation 3 and table 2.1 respectively. There are three variables central to this model, these are the quality reject ratio q_Q, downtime ratio q_S, production pace reduction ratio q_P, and are an index for the main causes for slower or less efficient production. Their effect on the part cost is such that an increase in their relative value would have a direct negative consequence on the production cost. Conversely, a lower value for either of these variables will cause a reduction in the part cost. Additionally to these ratios, the parameters that are of interest when calculating part cost accounting for the cost of the facility, are the cost for running equipment (Inclusive of the equipment´s cost itself) k_{CP}, and the cost of equipment while standing still k_{CS} (Ståhl and Windmark 2021). These two cost parameters can be defined in different ways depending on the application and might be inclusive of other cost connected to the facility; furthermore, these costs depend on the total yearly production volume and should therefore be calculated accordingly. Section 7.5 presents a practical application of this cost model, where the definition of all relevant parameters is elucidated.

$$
\begin{aligned}
k = {} & \underbrace{\frac{k_A}{N_0}\left[\frac{1}{n_{pA}}\right]}_{\text{Tool Cost}} + \underbrace{\frac{k_B}{N_0}\left[\frac{N_0}{1-q_Q}\right]}_{\text{Material Cost}} + \underbrace{\frac{k_{CP}}{60N_0}\left[\frac{t_0 N_0}{(1-q_p)(1-q_Q)}\right]}_{\text{Cost of Production}} \\
& + \underbrace{\frac{k_{CS}}{60N_0}\left[\frac{t_0 N_0 q_S}{(1-q_Q)(1-q_p)(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_p\right]}_{\text{Equipment Cost During Downtime}} \\
& + \underbrace{\frac{k_D}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_p)(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_p\right]}_{\text{Salary Cost}} \\
& + \underbrace{\frac{1}{N_0}\left[K_{AUH} + K_{CUH} + K_{GUH}\right]}_{\text{Cost of Maintenance}}
\end{aligned}
\tag{3}
$$

3 Empirical Findings

The empirical findings section illustrates the current scenario in a descriptive manner which will be utilized as a foundation for the analysis and discussion presented in the coming sections. The data was gathered through personnel interviews, observations at the site as well as documents that were provided by the company. The collection of the data hereby disclosed spanned over a period of approximately 8 *months and includes historical information from the company that dates back to the last* 4 *years.*

3.1 Company Description

The company hosting the research presented in this paper is a global manufacturer of breaking systems and components for the automotive transport industry. In this context, the manufacturing of brake calipers is a central part of the study. The market for this products is subject to the high demand and competitiveness of the automotive industry; thereby, a constant effort to continuously improve and refine production methods is a necessary strive to remain on top of the competitors. Additionally, the rising awareness for sustainability calls, now more than ever, for a more efficient and conscious use of resources. The current production is ought to expand to accommodate the growing demand and the re-shoring of production volumes to this region hence, offering the opportunity to make valuable improvements to the already existing production site. Moreover, having reached full capacity, the planning for development and expansion at the facility calls for prompt and effective solutions to the chip carryover problem.

3.2 Production Context

The following subsections aim to illustrate and contextualise the industrial scenario in which production occurs by discussing the processes, manufacturing strategies, and the current challenges for the production organization. As this is so often overlooked in similar reports, a brief presentation of the type of products that are manufactured is included in this paper as it was proven beneficial to establish a link between the product and production. This section aims to provide a better understanding of what challenges can be encountered and what are the limiting factors induced by the final purpose of the manufactured parts. Comprehension of the product geometry and its function will be central in grasping the challenges of the project as well as the analysis discussed in section 5 and 6.

3.2.1 The Product

At this facility, different models of brake calipers are produced for different customers, with different requirements and scaled to a set of distinct dimensions. In all cases, brake calipers are manufactured in a left and right orientation to fit the functional requirements of the application. The bulk of the production volume is set by the 22" (22 inches) caliper design which is currently available in two different models (According to the brand names

Haldex and *SAF*), or by customer´s requirement. Figure 3.1 presents an image of a right hand 22" caliper, as a casted blank on the left, and a fully assembled brake caliper.

Figure 3.1: Casted blank prior to machining, and fully assembled caliper ready to be shipped to the customer.

While there is no major difference between calipers branded as Haldex or SAF, and all models are based on a similar design. The right and left orientation castings differ in the placement of some of the features relative to the main symmetry plane for the brake caliper. Figure 3.2 provides a section view along the horizontal plane, which illustrates the inside geometry of a SAF right caliper after machining and surface coating but prior to assembly. The left hand version of the same caliper present the same geometry, mirrored along a vertical plane; different size calipers mainly differ in the measurements and shape of some selected features.

Figure 3.2: Cross section of caliper housing (SAF model in the right hand orientation).

3.2.2 Production Processes

The core production processes for this product consist of casting, machining, coating, assembly, and other minor manufacturing steps in between coating and assembly. While machining is the central activity at the facility, the casting procedure as well as the supply for most of the minor components in the final assembly are outsourced. The coating procedure and required chemical preparation of the the machined parts are performed on-site within a separate and dedicated facility. Functional testing and other inspections are conducted on each individual caliper at various instances and manufacturing steps. Additionally, a final quality assessment is performed to make sure the brake caliper will operate correctly once installed. In this section, some of the presented data originates from the older machine centers present on site and referred to as *Heller*, from which it was then transferred to the newly implemented *LiCON* machining center which constitute the *LiCON cell*. While this information might not be entirely up to date, given the changes and improvements which might have occurred over time, it can be considered as a gross indicator of the ongoing production parameters. Additionally, as the expertise at the company originates from these older machines, having a full view on these parameters can provide insights on how the LiCON cell came to be. Aspects concerning the LiCON cell are fully described in section 3.3.1.

3.2.3 Material Properties

The choice of material for the casted blank and brake caliper is a GGG-series ductile cast iron. The composition for this alloy is presented, element by element, in table 3.1; where the ratio is defined by the element mass and the remaining share is constituted by Fe, and in a negligible portion by impurities.

Element	C	Si	Mn	Mg	P	S	Cu
Share [%]	$2.5 - 3.6$	$1.8 - 2.8$	$0.3 - 0.7$	≤ 0.08	≤ 0.1	≤ 0.06	≤ 1.5

Table 3.1: Chemical composition by mass percentage.

Ductile cast iron´s relatively high hardness and ease to manufacture a product with, make it more desirable compared to other casted alloys; its mechanical properties are illustrated in table 3.2. Generally speaking, cast iron is well known for its short chipping behavior and relative ease of machinability; while ductile cast iron behaves similarly, it does not have as great chip breaking characteristics as the traditional grey cast iron (Ståhl and Seco Tools 2012).

This alloy however, provides the user with an extremely good compromise between mechanical properties for the finished product, cost, and machinability. Therefore, this and similar types of cast irons, are well employed in the manufacturing of components for the automotive industry; especially in trucks and heavy vehicles. The material utilized for the production of brake calipers at this site, has the same alloy properties previously illustrated but is subject to a ball blasting treatment that only affects the external and outermost surface layer of the workpiece.

Characteristic	Value	
σ_{max} Tensile strength	600	[MPa]
σ_y Yield strength	370	[MPa]
E Young's modulus	170	[GPa]
δ_{max} Critical elongation	3	[%]
R_m Fracture toughness	$600 - 820$	[MPa]
HV Hardness	$200 - 260$	[-]
k Thermal conductivity	$22 - 45$	[W/mK]

Table 3.2: Mechanical properties of the workpiece material (Ståhl and Seco Tools 2012).

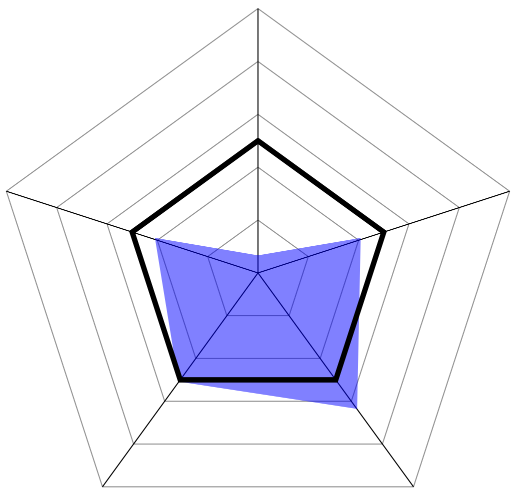


Figure 3.3: Machinability diagram for the workpiece material with 42CrMo4 as reference; adapted from Andersson and Ståhl (2007).

3.3 Manufacturing Context at Site

Machining operations constitute the central activity for the manufacturing of brake calipers at the site. In a strive towards increased productivity, a good balance between machining centers and external handling equipment has been found in the cell concept. Section 3.3.1 will dive deeper into the setup of this cell which from here on will be referred to as the *LiCON cell*. On the other hand, section 3.3.2 will expand on the remaining processes which while not being central to this study, are relevant for a complete understanding of the manufacturing context. Section 3.4 will continue with greater detail on how machining operations are conducted inside the LiCON cell, as well as how current interventions address the chip carryover phenomenon.

3.3.1 Machining Cell Layout

The machining operations for brake calipers at this site are conducted in the so called *LiCON cell*, consisting of 5 milling centers with supporting robotic arms and automation systems. The material is transported by a conveyor system that loops around the cell from the loading area, to the individual machines, and off to the unloading area where the machined parts are then positioned onto a pallet. The machine placement is scattered across the outside perimeter of the conveyor layout while the large automated robotic arms are placed by the area defined by the conveyor. Three robotic arms are located by the milling centers and are dedicated to picking and placing the workpieces from the conveyor to the machine and vice versa, while a fourth robotic arm occupies a more central position and is responsible for unloading parts from the conveyor and other operations. The loading of parts that need to be machined is done by the same robotic arm that serves one of the machines ($L1$), and occasionally manually by the operators, for smaller batches of different size brakes. Each machine is individual in the sense that they all perform the same sequence of operations. i.e. each component will only be processed by one of the machines in the cell. Inside the cell, the blanks and the machined parts are handled exclusively by the automated robotic arms. Additionally, there is an automated measuring center integrated in the cell, which is responsible for inspecting sampled machined components for compliance with dimensional tolerances. The complete layout can be visualized in figure 3.4.

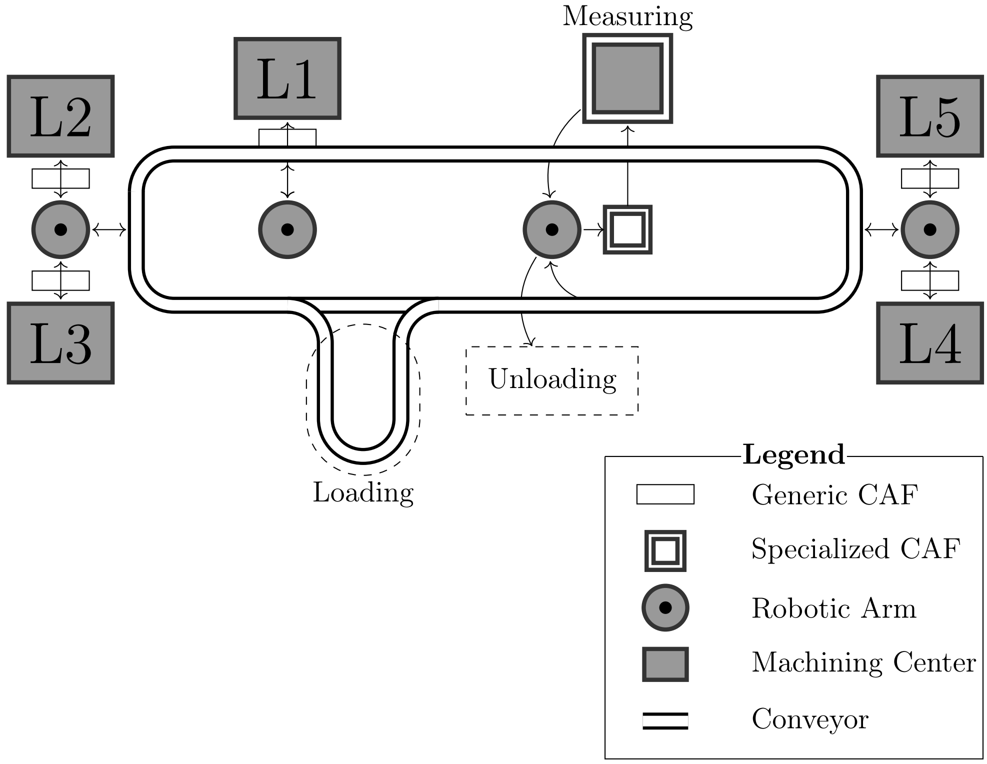


Figure 3.4: Layout of the LiCON manufacturing cell.

Compressed air fixtures (CAF) were developed to address the removal of persistent chips on the machined calipers; these fixtures are placed by each and every machine and are able to accommodate two parts at a time. The chip clearing operation is performed in a close box via the action of compressed air nozzles therefore, the name CAF. Along with CAF, each station presents fixtures to temporary rest components prior to machining. As the calipers are picked up from the carrier on the conveyor, this location functions as a buffer prior to machining. Moreover, it supports the loading and unloading of the components in the machine and reduces the movements required by the robotic arm during this operation. Similarly to the *generic* CAF, there is an additional appliance for chip removal located in the center of the conveyor layout. This appliance can only operate on one caliper at a time and is exclusively adopted for calipers that will have to enter the measuring center for quality monitoring. This is a solution that also utilizes directed air pressure (via nozzles) to address chip removal in specific areas where the measuring probes will need to contact the workpiece.

The effect of this *specialized* CAF is greater and more tailored to the needs for this location, yet it requires a relatively long time and only removes a minority of the chips present on the workpiece. An image of the central device (As well as the nozzle placement in each of the CAF) is presented by 3.9. As already mentioned, this central appliance is dedicated for the removal of chips prior to probing in order to avoid possible interference between the measuring probes and chips that persist on the surface of the workpiece, hence providing false readings. Similarly, the calipers are placed in this appliance with the aid of a robot arm. This arm has overcapacity that is currently allocated to a robotic movement ("shaking") of calipers for further removal of chips that might have remained trapped in the inner geometries of the machined workpieces.

3.3.2 Other Processes

Other processes are conducted at the facility to complement and integrate with the manufacturing of brake calipers. Such processes are referred to as downstream processes and are not of interest for the scope of this project but include functional testing and inspection of the components prior to their assembly. Additionally to machining, the site hosts a electrochemical deposition coating (EDC) station that is responsible for the surface treatment and coating of all brake calipers and caliper carriers that are produced at the facility. While this process is quite involved and requires a dedicated area due to the presence of chemicals, its location on site provides extensive benefits including reduced supply chain, shorter lead times, and lower environmental impact compared to third party suppliers for this service. Quality inspections play another important role, both in the machining area where tolerances are controlled automatically by automated measuring devices, and in general, the presence on site of a dedicated quality department ensures the highest standards in the finished products and during all manufacturing steps. Additionally, the location hosts a large research and development center where new and ongoing products are designed, prototyped, and tested, to continuously improve the assortment of braking solutions available at the company and meet future challenges. Finally, all parts converge in three production lines where the brake calipers are assembled and inspected before being shipped to the customers.

3.4 Machining

Calipers are machined in pairs of two at a time inside each of the LiCON milling centers. The whole machining process requires circa 35 minutes, of which approximately 1/3 is directly connected to active machining operations, from unloading of the pallet to exiting from the LiCON cell on a new pallet. In total, during this period of time around 1,37 kg (Approximately 9% the total weight of the casting) of material is removed in the form of chips from each of the calipers. Figure 3.6 summarizes operations within the LiCON cell and their relative duration. Since each of the machining centers is capable of machining two parts simultaneously, the Duration of Operation, DOO is to be considered for two parts. The cycle time per part can be obtained by dividing the sum of all DOO by two. Figure 3.7 also illustrates the percentage of the total machining time that each operation requires (DOO [%]), together with a brief description of the operation.

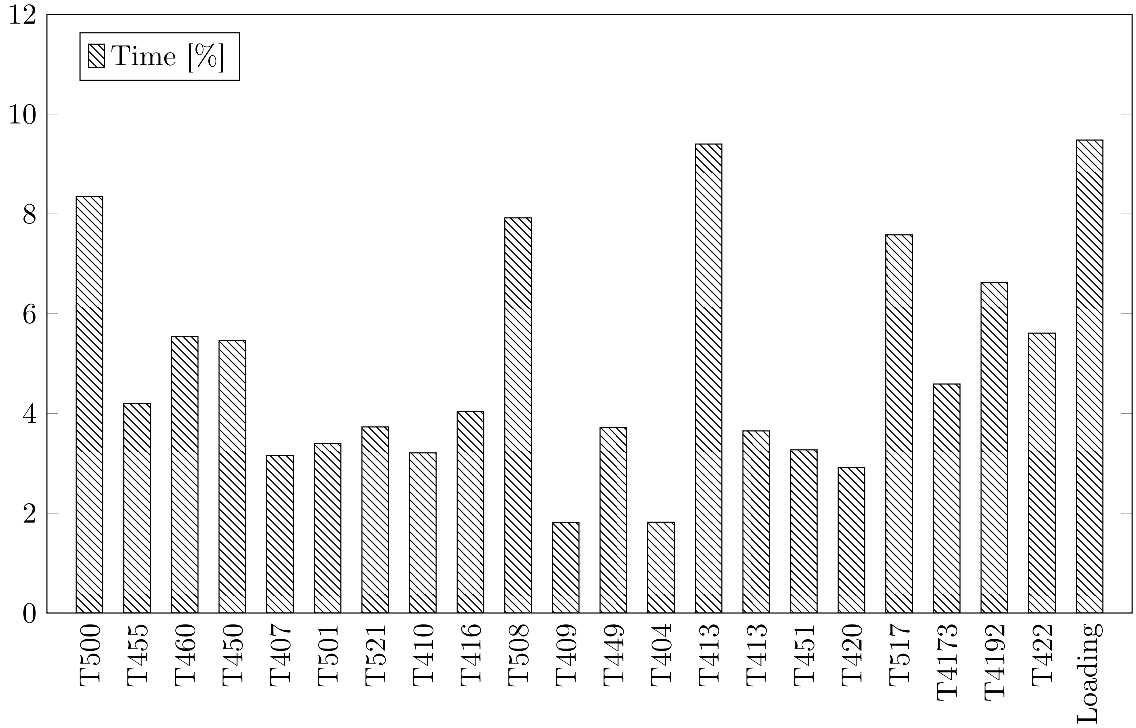


Figure 3.5: Duration Of Operation as percentage of the cycle time for LiCON 3 (2021) arranged by tool code.

3.4.1 Sequence of Operations

As previously mentioned, the machine time constitutes only a fraction of the total time (Throughput time) necessary for a pair of parts to go across the LiCON cell and undertake all the planned machining operations, as well as loading/unloading, measuring, and cleaning. Figure 3.6 proposes a timeline for all events that take place in the LiCON cell and their duration (The duration of measuring operations was not included in this analysis as it is only performed on a limited number of sampled parts and does not affect the overall productivity of the cell).

As it can be noticed in figure 3.6, there is a waiting time of circa 2 cycle times between the time the blank is unloaded from the pallet and enters the LiCON cell, and the moment machining operations begin. Such observation suggests that the handling equipment (Robotic arms and to a minor degree the conveyor belt) see relatively long periods of time between operating sequences. Whether it was originally considered and pondered upon the automation's load cycle, or it simply happened to be, this aspect could be of significant interest for future implementations. Specifically, the addition of another machine on the same automated handling system could be evaluated to potentially ensure a higher degree

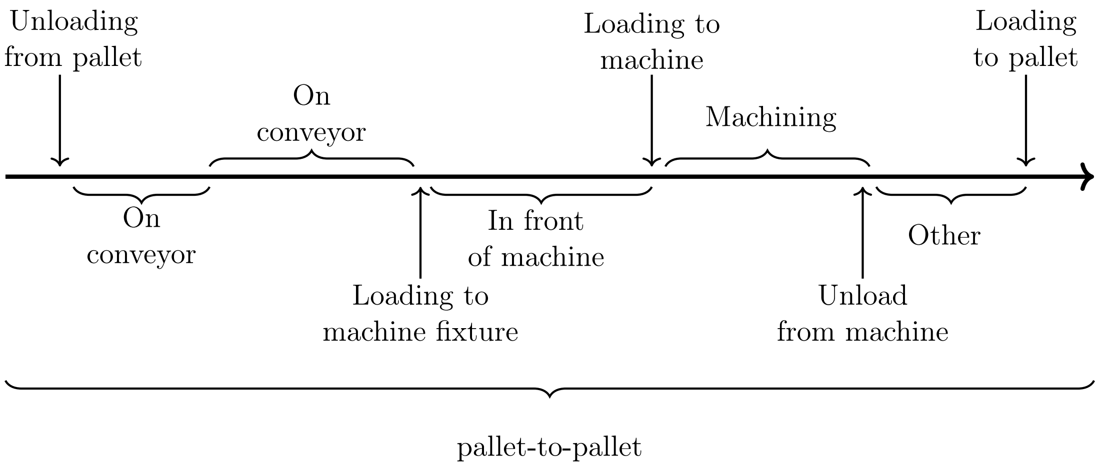


Figure 3.6: Sequence of operations in the cell.

of utilization for the equipment. Nevertheless, it should be noted that to a certain extent, the presence of an internal buffer can absorb standstills due to the change of pallet and therefore be beneficial. Moreover, the presence of non-utilized time where the parts are standing in front of the machine, and in proximity to the CAF (compressed air fixtures) for chip removal, could potentially be employed for additional cleaning/chip-removing operations.

Figure 3.5 presents a graphical overview of the duration of each operation, as distinct by the utilized tool, which is specified on the horizontal axis of the chart with an internal code. The final operation identified by *Loading*, corresponds to the time required by the automated robotic arm to unload the machined parts and load new workpieces inside the machine. Furthermore, tool T422 does not perform any machining operation but is merely a flushing head that in principle washes away any remaining chips from the machined part. It functions as a directional nozzle for fluid that is pumped through the spindle of the machine. This operation is not only consuming a large share of time (Almost 6% of the cycle time) but it is also not entirely effective. Therefore, any future development or changes to the machining sequence should be aimed to reduce the duration and potentially remove the need for such operation, especially given the current need for the company to expand their production capacity.

All machining operations that take place inside the LiCON machines are listed in figure 3.7 where their duration (DOO - Duration of Operation) is expressed as percentage of the total cycle time. However, this figure does not distinguish *value/non-value adding time*; whereas value adding time is time spent in the machine to actively remove material from the workpiece, non-value adding time is spent in operations that are not directly influencing the product yet, movements necessary for the machining program such as placement of the workpiece or tool changes. Such distinction in the cycle time is not available operation-by-operation and therefore, non-value adding time is presumed to be equally distributed across all operations. This separation is done globally on the complete cycle time and it is visually presented in figure 3.8. It can be observed that the non value adding time sums up to approximately 30% of the cycle time. This information must be taken critically as

Tool	DOO[%]	Feature
T500	8.35	Milling operation 1
T455	4.20	Drilling operation 1
T460	5.54	Operation 2
T450	5.46	Operation 3
T407	3.16	Milling operation 2
T501	3.40	Drilling operation 2
T521	3.73	Milling operation 3
T410	3.21	Drilling operation 3
T416	4.04	Milling operation 4
T508	7.92	Predrill hole 1
T409	1.81	Ream hole 1
T449	3.72	Predrill hole 2
T404	1.82	Ream hole 2
T413	9.40	Operation 4
T451	3.65	Operation 5
T461	3.27	Operation 6
T420	2.92	Milling operation 5
T517	7.58	Drilling operation 4
T4173	4.59	Predrill hole 3
T4192	6.62	Ream hole 3
T422	5.61	Flushing operation
–	9.48	Change of pallet

Figure 3.7: Specification of tool operations and Duration of Operation DOO for LiCON 3 (2021).

the value for this figure relies on data from a cutting sequence for the machining center Heller 4 in late 2019; the information could therefore be outdated and/or not transferable to the LiCON machining centers. Nevertheless, this data was believed to be interesting in qualitative terms and provides a rough index of the efficiency of the machining sequence. In general terms, a 70-30 distribution of value adding versus non-value adding time is considered to be an indication of efficient manufacturing.

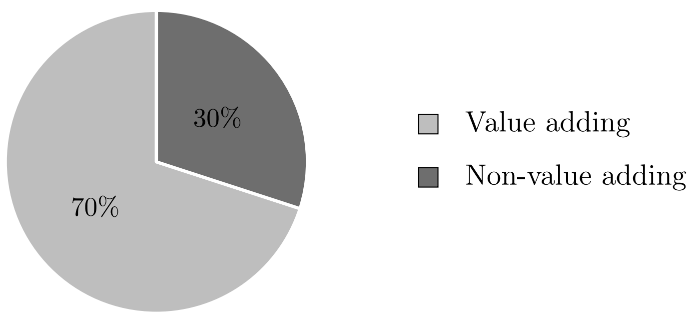


Figure 3.8: Value and Non-value adding time during machining (2019).

3.4.2 Cooling and Lubricating Solutions

Cooling and lubrication of the machine and cutting process is done automatically throughout the cycle as each LiCON machine has a dedicated cooling system capable of providing high volume and/or high pressure coolant. The cutting fluid is a water-oil emulsion that is delivered both to the cutting area and to other areas of the machine to aid the removal of chips, and has the dual purpose of lubricating and cooling. Both spindles in the machine are equipped with an internal cooling solution that allows the fluid to be delivered through the tool itself and directly to the cutting area, where it is most needed. High pressure fluids are also effectively employed to remove chips to a greater extent (More on this in the following sections). When this is the intention, direction, pressure, and flow of the cutting medium must be carefully addressed to provide an effective action.

The oil share to water ratio in the cutting fluid is engineered to minimize the wear on the tools and at the same time minimize the need for larger volumes of lubricants. High concentrations of oil are not only expensive to maintain and dispose but can also cause the fluid to behave more viscously. This could potentially be problematic as increasing viscosity strengthens the adherence properties of the fluid and cause chips to bind more easily to the surface they are resting on. The adhesion phenomenon can be more problematic if there is sufficient time for the fluid to set and start drying. Given the relatively large time share between the end of the cycle and when the parts exit the cell, it would be beneficial to anticipate the cleaning of the workpieces as much as possible; this way, any level of adhesion would be minimized to where it would not affect the following operations. As already mentioned, a lower concentration of oil is to be preferred; however, if there are leakages of fluids such as hydraulic oil or other lubricating means from the machine, the concentration of the cutting fluid would tend to increase over time, as more oil finds its way into the cutting fluid. Likewise, the inevitable evaporation of water from the solution and the loss of fluid every time a part exits the machine, call for regular topping off and adjustment of the solution´s concentration. Hence, an oil concentration that results in low enough adhesion strength needs to be identified in combination with a feasible chip removal procedure.

3.4.3 Current Solutions for Chip Evacuation

The current production set-up embraces three main interventions that were put in place to manage persistent chips on the machined parts. The first two solutions are dedicated and permanently installed apparatuses which utilize compressed air as a cleaning medium. On the other hand, the third approach consists of an additional programmed motion of the one robotic arm that handles the unloading of all parts from the LiCON cell. The two compressed air fixtures (CAF) are quite different from each other despite them both relying on the same technology.

The first apparatus is present at each machine center and it is utilized directly after machining of the calipers. On the contrary, the second solution is placed later as a second round of chip removal, prior to entering the measuring station on the premises of the Li-

CON cell. Therefore, only parts that are bound to be inspected in the measuring station undertake this additional cleaning step. For this reason, the primary aim of this apparatus is to clear of possible chips, those areas that are of interest because of their strict tolerance requirements. The nozzles in this solution are therefore placed to specifically address the areas where dimensional tolerances are going to be inspected. This operation is performed to avoid interference with the measuring probes and potential misreadings caused by persistent chips. To clarify, all calipers will consequently not undergo the cleaning operation at this station since measurements are not conducted on all calipers in the cell. Additionally, this set-up requires a longer cycle time and a number of specific fixtures. Hence, while studying this apparatus can be interesting to understand chip behaviour, this solution cannot be scaled to cover all the parts machined in the cell. Moreover, the cleaning procedure performed at this stage is only focused on limited areas and not optimized for a complete cleaning of the machined caliper. The compressed air fixtures are illustrated in figure 3.9. On the left side it presents an image of the first *generic* solution, installed by all machine centers and across which all machined parts go through.

The second *specialized* fixture is illustrated on the right side; this fixture is unique in the LiCON cell and only a limited number of parts are affected by this operation. It can be noticed how different the nozzles in the two apparatuses are, both in terms of positioning and type of nozzle employed. In both cases, the CAF currently employed in the LiCON cell have only been marginally successful in removing chips from the machined parts.

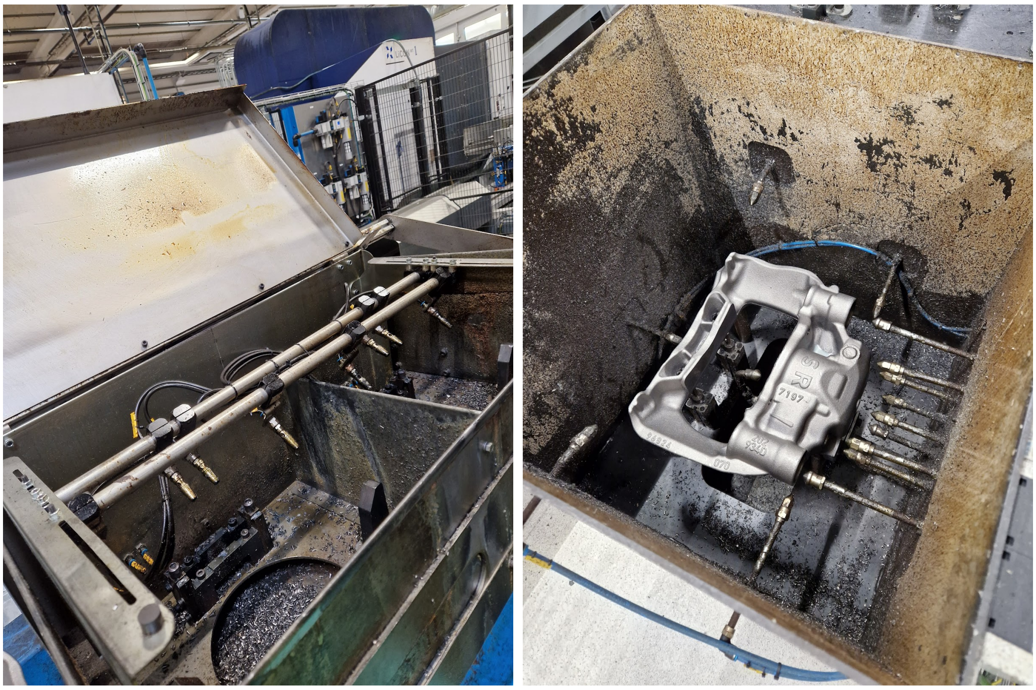


Figure 3.9: Compressed air fixtures (CAF) for chip removal; generic CAF (Left), specialized CAF (Right).

The LiCON cell presents a multitude of robotic arms that are required to load and unload pallets containing brake caliper, as well as handling the workpieces to and from the machining centers and compressed air fixtures. Specifically, there are two robotic arms located in the central area of the cell that are predominantly dedicated to unload the castings from the incoming pallets and load the machined parts back onto the pallets exiting the cell. One of these two arms differs from all other robotic handling solution as it currently carries out the task of shaking the machined parts, in addition to its ordinary functions and prior to unloading them onto a pallet. Figure 3.10 presents an image of the robotic arm while performing the so-called "shaking motion" for the removal of chips. This additional feature was implemented to aid the removal of chips that could have remained stuck in the inside geometry of the workpiece, and was not originally ideated with the original LiCON cell. Its development was made possible by the low utilization rate/presence of standstills of the robotic arm at hand, which is first and foremost utilized to place the machined calipers onto the pallet as well as to transfer the calipers that are going to be measured into and out of the specialized compressed air intervention designed for this purpose. The overcapacity of this arm has therefore been re-allocated to the robotic "shaking" motion; this operation is performed over a tray, before placing the finished parts onto the pallets that will then exit the LiCON cell. Currently the program that was implemented to perform this operation handles the machined part in such a way that any chips captured in the inside geometry of the workpiece would have difficulties to come out. This is because the angles/positions utilized in this motion do not match with these necessary to let chips come out of the inside geometry of the brake calipers.

Figure 3.10: Central robotic arm in the LiCON cell performing the "shaking motion".

3.5 Chip Varieties and Distribution

Because of its nature, the casted blank for the workpiece requires a significant amount of material to be machined away in order to obtain the required finished product. The cast model has been designed to minimize the required removal of material during machining and at the same time, to be *castable* in an efficient manner. While excess material is expensive for many different reasons (Machining, casting, transport, etc), it is also necessary to ensure a correct pour, free of porosity or cold welds and with enough material to account for variation in the casted parts. Therefore, the required operations produce a relatively large volume of chips in different shapes and sizes. Chips found in the manufacturing site are categorized and illustrated in figure 3.11.

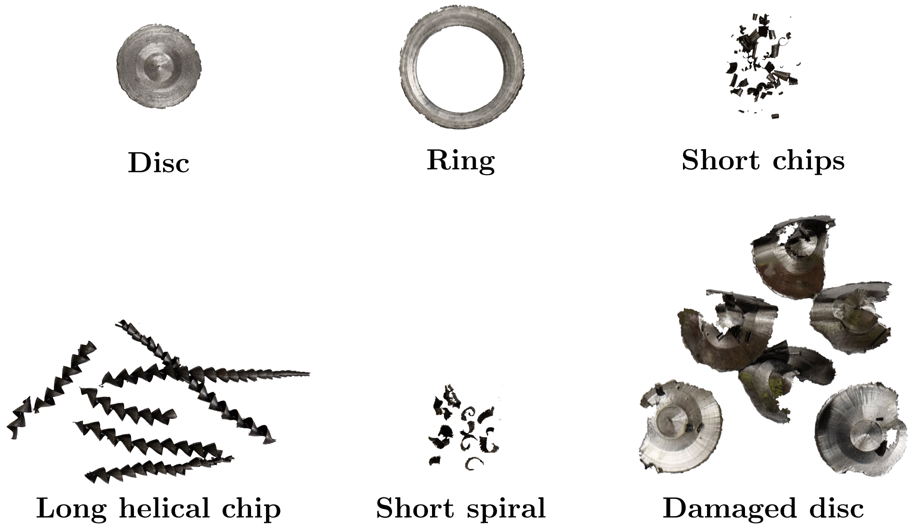


Figure 3.11: Chip and burr varieties from the machining process.

Among all the different variations, those chips classified as *short chips* constitute the majority of the removed material and are the main responsible type of chip for wear on conveyor belts and supporting equipment; an example of wear on the conveyor is presented in figure 3.12 (Right). On the left side of figure 3.12, a large amount of chips is present below the conveyor line, where the belt meets the motor. This suggests that the small chips do not only travel along the belt but also work their way in between the moving parts and the structure of the conveyor.

Observe that in figure 3.11 "chips" labeled as *Disc* are technically burrs rather than chips, and would be more correctly defined as tool exit burrs. Additionally, as it will be more clearly elucidated later on (Section 5), the *Disc* and *Ring* are both products of the same operation while the *Damaged Disc* can be associated to a different feature, and is by all means, a tool exit burr in the form of a disc that is not completely formed. The decision to consider these burr formations collectively as chips is linked directly to the problem formulation of the chip carryover phenomenon, as explained in section 1.2. This way, not only the terminology is simplified throughout this report but also, as from a practical perspective both sources of "chips" incise equally on the manufacturing process and are therefore addressed as one.

The various chip types were collected and mapped at different stages and locations of the production flow, to gain a comprehensive understanding of the chip carryover phenomenon and the effectiveness of the different mechanisms that were designed to handle

Figure 3.12: Presence of chips on conveyor belt and equipment.

it. Moreover, some of the chips were persistent enough to be located during testing which is why some coated chips such as those presented in figure 3.13 were found.

Figure 3.13: Coated chips found in testing after coating operations have been completed at the EDC facility.

The distribution of the chip types presented in figure 3.11 and present across the whole production facility, is mapped and sorted in table 3.3. This illustrates how removal of chips is more than just random and that different mechanisms have different strengths and weaknesses regarding certain chip types specifically. Metal chips do not simply diminish gradually along the production flow, but rather at certain stations depending on the chip variant and the handling operation of the workpiece at that point in production. This is true both for chip type and for chip volume or quantity, as it will be addressed later on in this report.

	LiCON	Generic CAF	Tray	Specialized CAF	EDC	Downstream Processes
Disc	✓	✓				
Ring	✓					
Damaged disc	✓		✓		✓	✓
Long Helical	✓	✓	✓		✓	✓
Short Chips	✓	✓	✓	✓	✓	
Short Spiral	✓	✓	✓		✓	

Table 3.3: Chip types and distribution across the facility.

4 Problem analysis

The problem analysis presents the current implications related to the chips carryover phenomenon and acts as a foundation for the potential improvements presented in section 5 and 6. Henceforth, this section is a pivotal point for the progress of this study, as it constitutes a transition point from data gathering to practical application. The content remains of empirical character but was collected in sequence with the data presented in section 3 and partially simultaneously with the analysis presented in section 5.

4.1 The Phenomenon: Chip Carryover

In the current production scenario, chips from the machining operation are carried over to the subsequent stations causing higher wear on handling equipment and failures in the downstream processes. In an attempt to minimize this issue, some changes in the machining sequence have caused the cycle time to increase; this however, negatively affects the production performance given the already full capacity at the facility. Figure 4.1 graphically illustrates the phenomenon and its cause-effect sequence of implications across the production floor. The roots of the chip carryover problem can be found in the machining operations where the chips are formed. Nevertheless, its effects can be observed growing across all the processes/locations downstream in the production flow. Implications on each of manufacturing sub-steps are addressed in section 4.2.

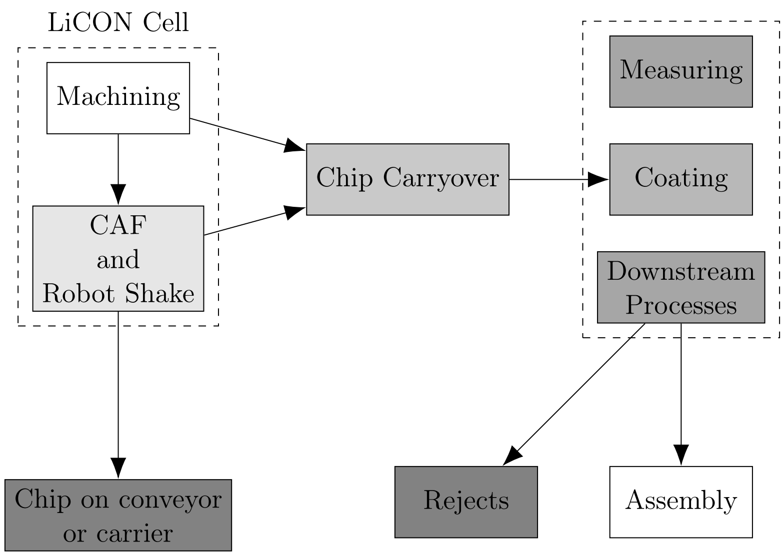


Figure 4.1: Mapping of phenomenon.

4.2 Problems Caused by Chip Carryover

The chip carryover phenomenon causes a number of issues within many aspects of the manufacturing process at the facility, ranging from chips being spread out across the production site, to failures in downstream processes up to the assembly lines. The following subsections illustrate and discuss the main areas of concern, as identified in the definition of the phenomenon in section 4.1.

4.2.1 Issues Related to Production

A historical record of all scrapped parts was investigated and presented in respective quarters by figure 4.2. In order to evaluate the the presence of trends and development over time, these results were normalized to reflect failures of current production volume during previous quarters; by doing so, the values can be compared to each other at the same time. Consequently, no distinct trend was identified based on the normalized failure volumes. Nevertheless, inspection of scrapped calipers revealed that a majority of failures were due to casting blank defects or other causes such as a faulty fit in the fixture or tool failure. Although volume of failed components are significant in the production compared to that of other processes, indications of failures related to chips are absent. Additionally, failures in $Q-4$ 2022 should be regarded as an outlier or anomaly since the abnormal volume is partially due to continuous testing of new tools and cutting parameters which have resulted in a large portion of dismissed parts recorded during this period.

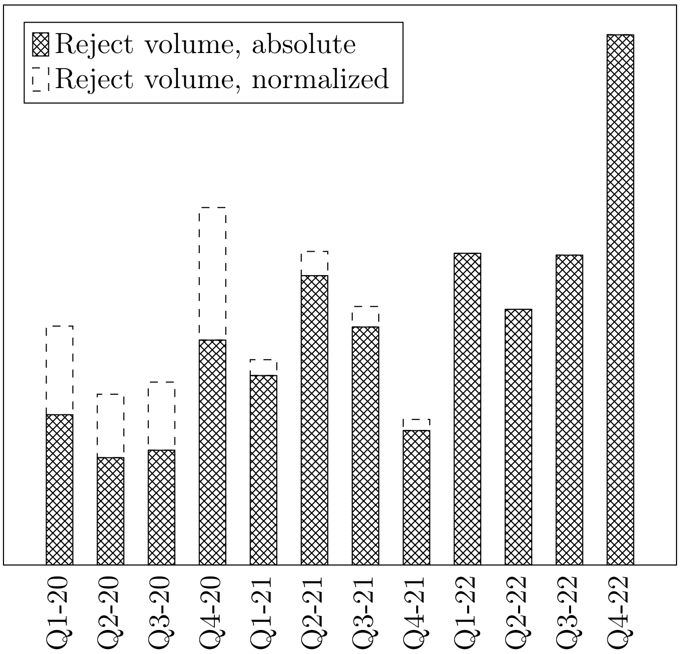


Figure 4.2: Failed parts in production, count and values normalized on the current production volume.

4.2.2 Implications on the Coating Facility

Machined components reach the coating facility via pallets. When the parts are picked up again to be placed on the carriers that will enter the coating facility, a large share of the chips that were carried over along with the machined part, tend to detach from the calipers and fall to the ground. A significant amount of chips was recorded in the area, which consequently requires the operators to perform additional cleaning. An evaluation of the volume of chips that affect the EDC (electro-deposited coating) station has been performed and is presented in table 4.1. If and when the chips do not leave the parts prior to coating, there is the possibility of them becoming connected to the surface of the workpiece by effect of the EDC, acting like a binder between the chips and the main body of the brake caliper.

The vast presence of chips at this location is primarily concentrated by the loading/unloading station, where the movement imparted to the part by robotic arms facilitates the removal of chips that rest on the surface of the workpiece and/or in the inside geometry. Disc burrs from the 19" brake calipers evidently seem to be more difficult to remove during machining than that of the 22" caliper; consequently there is a higher share of discs from the 19" removed at the EDC station. Further analysis of these discs is presented in 5.1.

Mass [kg]	No. discs [·]	Discs/Mass [1/kg]	Discs/caliper (22") [%]	Discs/caliper (19") [%]
8.15	63	7.7	0.785	1.13

Table 4.1: A quantitative assessment of the presence of chips in the EDC facility (Average reference values).

4.2.3 Other Implications on Downstream Processes

Failures found in the downstream processes are particularly problematic because of the accumulated cost of the work in progress from prior processing. Product defects are especially expensive in these later stages; rejecting parts at this point means that all effort up until that point will be wasted as the company currently does not consider it appropriate to rework parts (Both for safety and quality reasons, as well as too high cost connected to rework). Failures detected during tests performed at later stages of the manufacturing process are illustrated in figure 4.3.

Similarly to what discussed along figure 4.2, a close observation of the normalized data in figure 4.2 does not suggest the presence of trends in the distribution of the failed parts. These findings thus suggest that the failures are intrinsic to how the manufacturing and the specific operations are set up rather than being related to wear or similar phenomenons. The recorded failures that could be imputed to chips, where primarily caused by a defined type of "chips" illustrated by table 3.3. The only types found at these later stages were the discs and long helical chips. This may be due to the fact that short chips could be encapsulated in the coating or not present anymore at this stage, and are not problematic for the final assembled caliper. Nevertheless, the disc-type chips are without any doubt the principal reason for calipers being rejected during the testing of the caliper. Upon inspection, the discs found in these failed calipers were found to be directly linked to the machining operation of a specific feature in the workpiece. These particular disc-type chips are the damaged discs formed during machining of the second feature in figure 5.1. This burr is detached from the workpiece inside the caliper housing and is thereby, particularly problematic to remove from the inside geometry of the workpiece.

Furthermore, differences in chip carryover have been identified according to figure 4.4 depending on the left/right configuration of the caliper. This is not necessarily linked to differences in the design of the parts but could rather be because of different handling

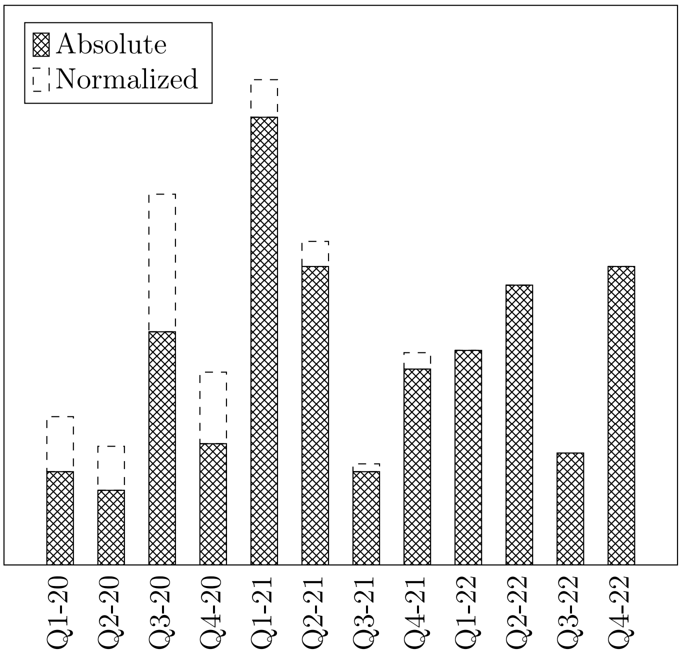


Figure 4.3: Failures in the downstream processes.

movements during and after the machining sequence. Similarly to the differences in the left and right perspective, the difference in failed parts between the two models was investigated. This discrepancy is illustrated preliminarily by figure 4.4 which however, does not provide a comprehensive overview because of the different volumes the two products are produced at. More interestingly however, despite having an overall similar behaviour, it was found that the SAF caliper model is more susceptible to chip carryover than the Haldex model in the right hand caliper orientation. Vice versa, the opposite is true for the left hand orientation. The right orientation constitutes 82% of the SAF models total failed parts during testing whereas the right orientation of the Haldex calipers has a lower value of 63% as illustrated in figure 4.4.

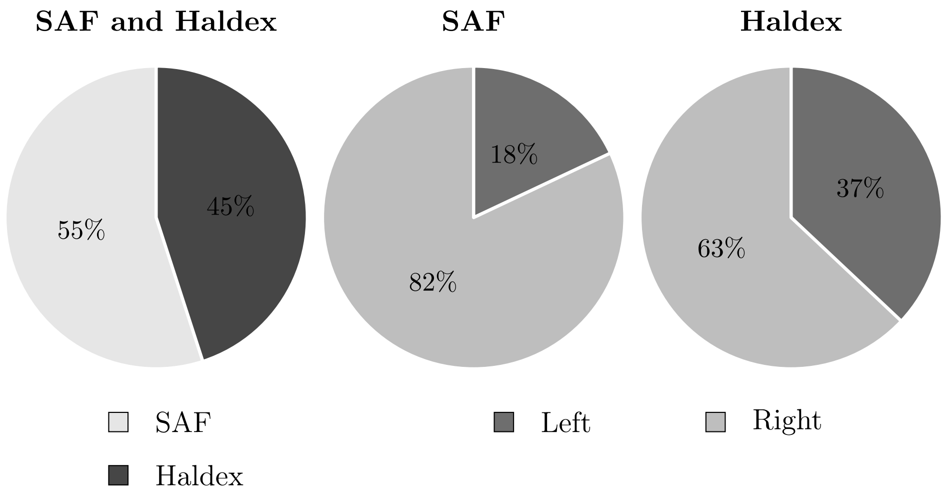


Figure 4.4: Representation of failures in the downstream processes due to chips in regards to cast model and orientation.

5 Linking Manufacturing to Chip Carryover

One of the major obstacles to effective chip evacuation is intrinsic to the nature of the milling process, where contrary to turning operations, the workpiece is stationary or semi-stationary. Whereas in a lathe, the majority of chips is naturally removed during machining by effect of the cutting tool deflecting the chips away from the workpiece and because of the centrifugal forces generated on the mass of the chips by the rotation of the workpiece.

A hindering role in the correct evacuation of the chips is played by the presence of geometrical features that could trap the chips inside the workpiece. When this is the case, rotational forces, compressed air jets, and flushing with coolant can have the double effect of evacuating the chips or contributing to getting them stuck into areas were the removal of chips may result arduous. Because of this, the handling sequence of the workpiece during machining operations, as well as machining parameters and cutting data, play a crucial role in determining the issue. On the other hand, one of the advantages of milling compared to turning, for the scope of reducing the chip carryover phenomenon, is how the chip forming mechanism occurs. Milling implies a natural chip breaking action dictated by the entrance and exit of the workpiece for each revolution of the cutting edge along the axis of the spindle. Conversely, in continuous turning operations, if the cutting tool remains engaged in the workpiece, chips are broken only by effect of extensive curling deformation and occasionally by the presence of impurities or weaker areas in the removed material. Therefore, in milling operations a majority of the removed metal volume is transformed into short(er) metal chips; making for some of the most manageable chips attainable. Nevertheless, there are some features on the workpiece that cause problematic chip types, for example in drilling operations with solid drills, or when a drilling operation causes formation of large burrs that detach from the workpiece.

5.1 Feature Analysis

The sequence of operations required to obtain the desired geometrical features in the finished product is rather extensive and a number of different machining strategies are employed in this program, including milling, drilling, short drilling, and tapping. While some of them produce chips that are easily removable from the workpiece, others are more problematic. This section will illustrate the linkage between different types of chips and the features of the workpiece.

The burr formation of the chips resembling a disc is a consequence of the cutting forces being higher than the support the structure has to offer. Thereby, the material gets pushed through in the form of large burrs (For the sake of simplicity, these burrs are often referred as disc burrs, or simply as discs) rather than being cut into smaller and more manageable chips. This phenomenon may also result in discs not fully separating from the workpiece but rather getting bent over their edge in proximity to the exiting surface of the feature. These discs are mainly formed during the drilling/milling operations of the holes highlighted as feature ① in figure 5.1. This feature is also responsible for the production of the *ring* chips illustrated in figure 3.11; the two-stepped insert drill creates this very unique burr

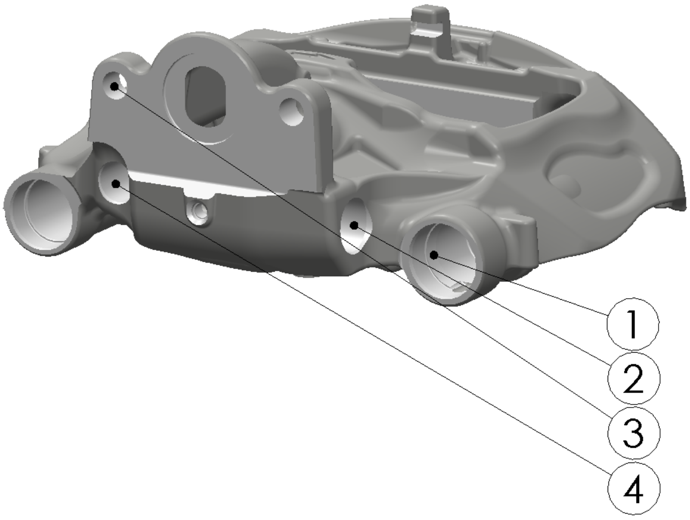


Figure 5.1: Operations resulting in different chip types.

configuration. According to interviews, evacuation of these discs has been problematic as they have a tendency to fall back into the inside geometry of the caliper's housing. Similar discs were previously also formed during machining of feature ② in figure 5.1. However, recent changes in the cast's design and tooling for this feature, have been such that the cutting edge breaches one side of the disc burr first, resulting in intermittent cutting and hence creating a chip that still looks like the disc but is not fully formed. In this study, these partially formed burrs are referred to as broken/damaged disc chips or burrs. Figure 5.2 illustrates the internal geometry of the casting from which the parts are machined, the highlighted area is where the partially formed disc burrs occur. The same detail is better represented by figure 5.3.

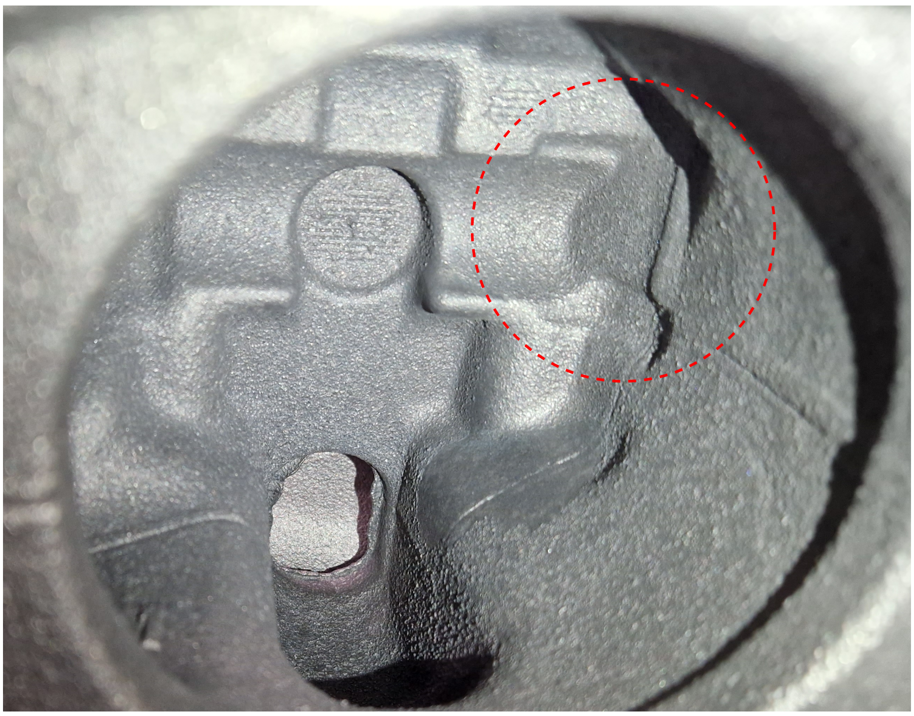


Figure 5.2: Internal geometry of part as casted.

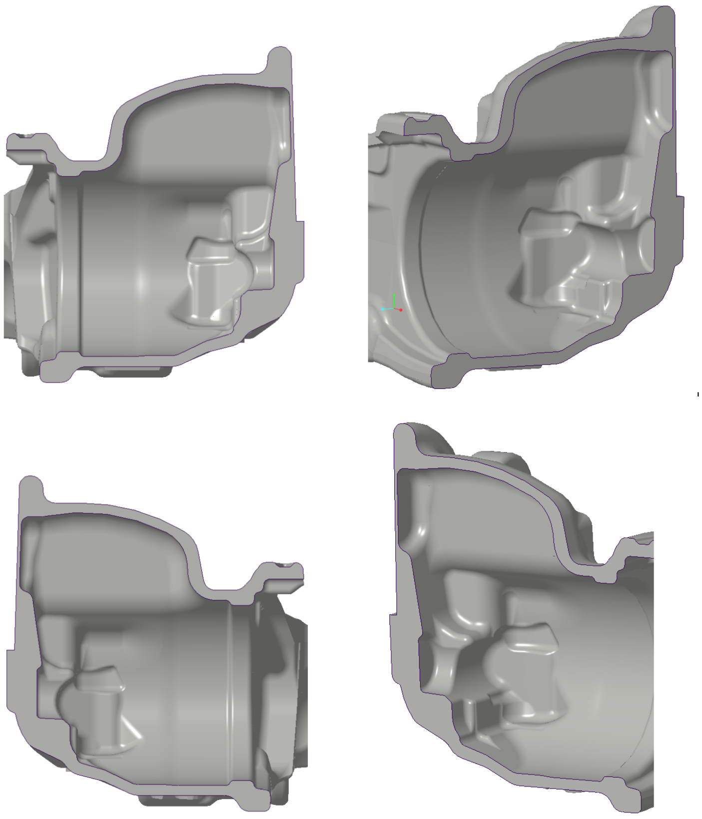


Figure 5.3: Details of the geometry as casted, in the area adjacent to feature ② (Left version above, right below).

Chips that are formed this way, or partially formed disc burrs tend to rest inside the workpiece as the process' fluid pressure and direction is generally not sufficient to effectively flush them out, and can potentially remain stuck. This type of chip is particularly problematic as it is found in all rejects in the downstream processes that are due to presence of chips. Partially damaged discs detach from the workpiece inside the housing and are prone to getting stuck between the internal pillar illustrated in figure 5.4 and the the bulk of the workpiece. This area is located on the opposite side, with respect to the section plane, of the feature where the disc is formed (Not visible in this sectioned representation), and due to its location, the pressure of the fluid exiting the cutting tool might facilitate the half formed disc reaching this area.

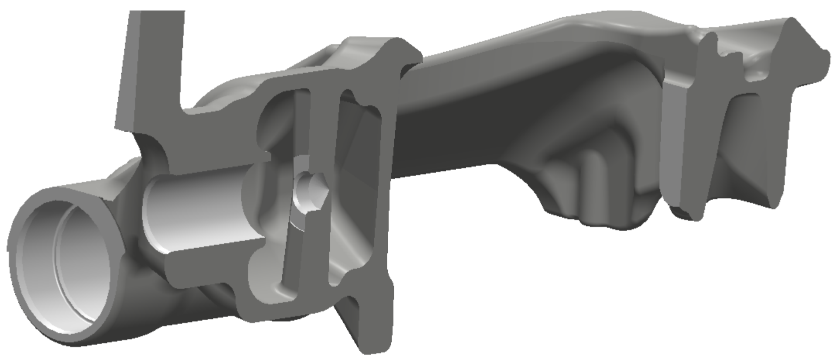


Figure 5.4: Internal pillar; section of the brake caliper.

Additionally, when the workpiece is mounted in the machining center via automatically actuated clamps, some areas remain covered and protected from the action of the cooling/lubricating fluid. Such zones are prone to the accumulation of smaller chips, as illustrated in figure 5.1. The short spiral and long helical chips are formed during drilling with a conventional double flute solid step drill of features ③ and ④ in figure 5.1 respectively. The long helical chips have proven to be problematic as they can aid the accumulation of shorter chips that later merge as the cutting fluid starts to dry out once the machining operations are completed. An illustration of the particular and problematic chips as well as the linkage to the features from which machining they are generated, is presented in figure 5.5.

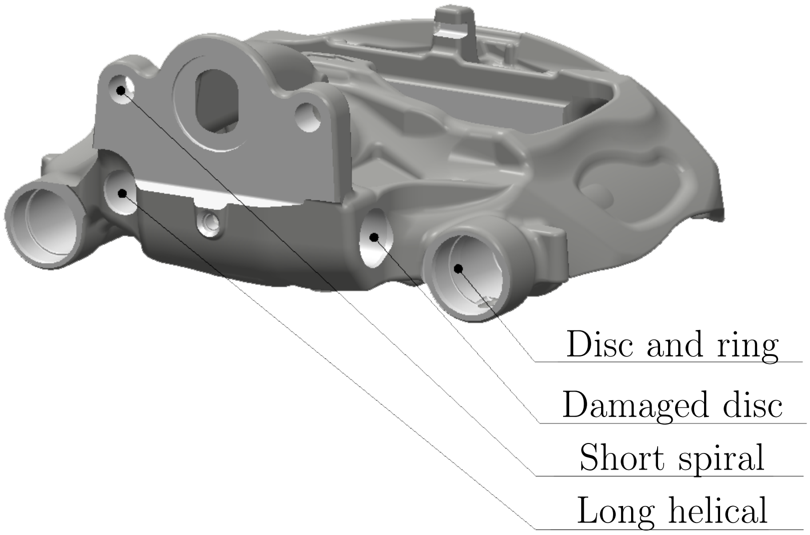


Figure 5.5: Linkage between type of chip and selected features.

While the inspection of the different cast orientations 5.3 has revealed no difference that could justify such distribution in the failure incidence as illustrated in 4.4, it is possible that different caliper orientations are handled in different ways. While this is not entirely relevant for today's production scenario (More extensively discussed in section 6), it might become important for the new manufacturing cell currently under development. Upon inspection of a CAM animation of the machining sequence, it was noticed that in newer LiCON machines, left and right calipers can be handled in different ways. In this simulation, feature ② in figure 5.1 is the last machining operation in the sequence and it forms the problematic damaged disc which can then remain encapsulated in the inside geometry of the caliper. During this step in the machining sequence, the right caliper is held semi-statically with slight rotation about its vertical axis as illustrated in figure 5.7.

Conversely, the left caliper model is machined upside down and rotated about two axes after the operation is completed; illustrated by figure 5.6. This motion is performed when there is still a significant volume of coolant in the caliper housing which is believed to aid the evacuation of the chips to a greater extent. Furthermore, it is possible that the flow of the fluid aids the process of loosening the rugged disc from the caliper housing, given its momentum and added mass. This would in part explain why there is a larger amount of

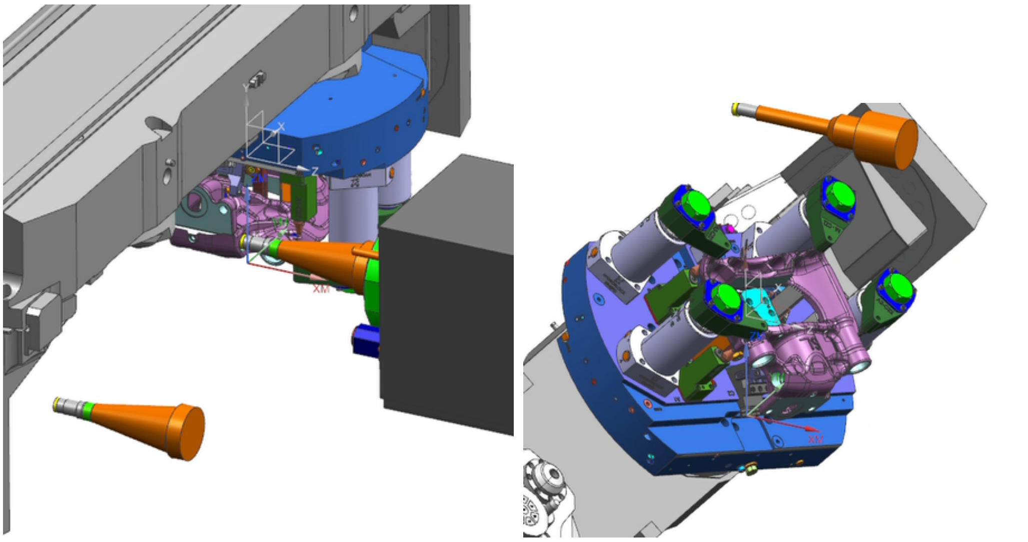


Figure 5.6: Left hand caliper motion post processing of feature ② in figure 5.1.

right caliper failures compared to the left version; however, the situation described above is only a simulation and does not describe the current production scenario. At this time, the production in the LiCON cell is carried out with both parts facing down like described above for the left hand caliper orientation. Additionally, there is no CAM file available for operations in the existing LiCON, making it difficult to conclude and document what the influence of handling is, if any. On this matter, the analysis on the current LiCON cell was performed by recording high speed videos inside of the machine and inspecting them at a later moment, like one would do with a CAM animation. Although critical, issues related to handling operations inside the machine center, could be limited by re-engineering the sequence of operations and how workpiece positioning is conducted inside the machine; this is specifically addressed in section 6.3.

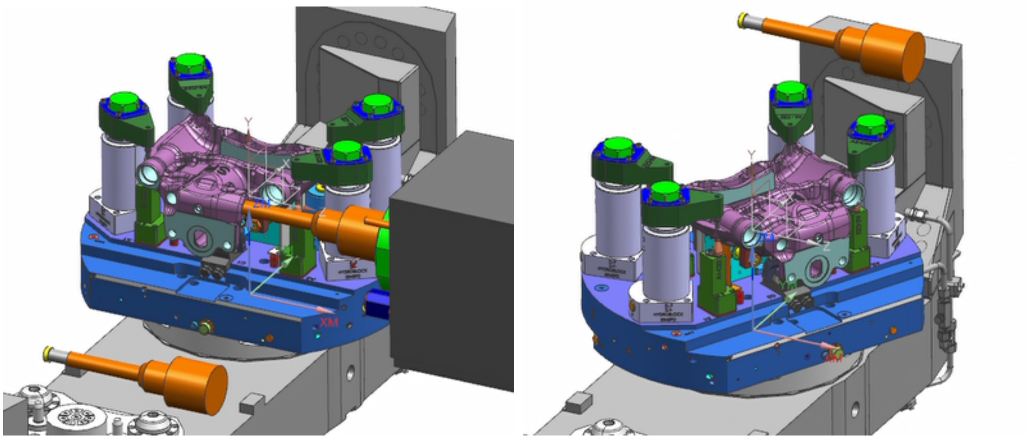


Figure 5.7: Right hand caliper motion post processing of feature ② in figure 5.1.

Analysis of a Salient Feature:

Machining of feature ② is considered to be the most problematic as this feature is directly responsible for failures in testing, as previously described in 5.1. The disc burrs produced during machining of feature ② consistently produces discs in two distinct appearances. The use of molds to manufacture the internal geometry of the caliper results in seam lines on the surface of the blank such as those illustrated in figure 5.8 (Note the parting lines on the casted surface, prolonged by the red dashed lines). These tracks were henceforth utilized to identify the chip formation behaviour by correlating the orientation of the chips to that of the blanks. Figure 5.9 similarly showcases the consistent presence of the seam lines on the chips. By identifying this correlation, it is possible to imply that the damaged zone on the disc chip occurs predictably in the same area every time. Therefore, an analysis can be performed with the aim of understanding how the topology of the casted surface would affect the formation of the chip, and potentially be engineered to be broken down in small chips rather than discs.

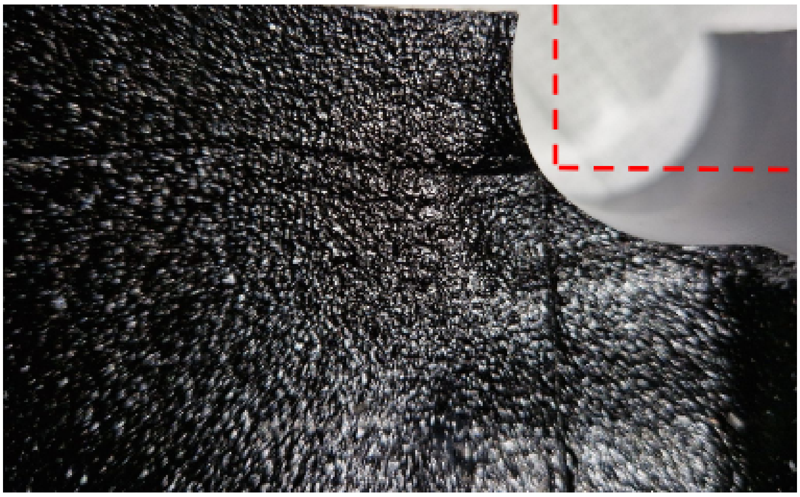


Figure 5.8: Topology of casted surface in proximity of feature ②.

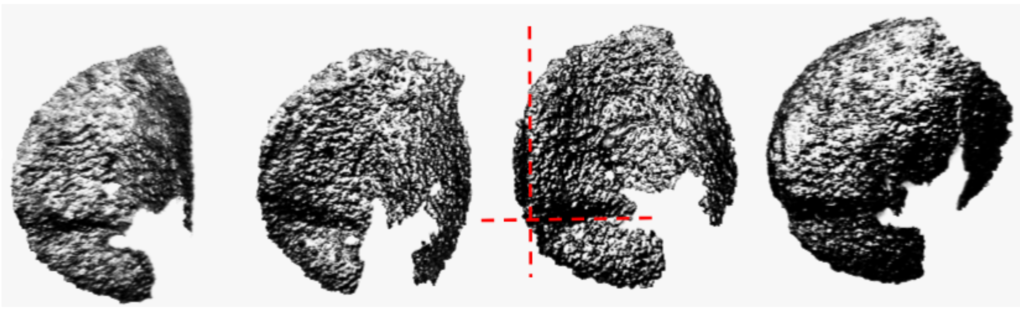


Figure 5.9: Burr formation and linkage to topological features of the casted surfaces.

Following the initial stage of chip characterization, different chip formation behaviors could be associated to the left and right calipers through a side by side comparison of the chip shape with the cast design topology 5.10. As presented in figure 5.10 the blank geometry is mirrored between the right and left hand version; this aspect, has a significant influence on the chip formation behavior as the rotational direction of the tool is the same for both caliper orientations. What this means in practice, is that because of symmetry in the casting, the two surfaces will see a relative tool rotation that is opposite in direction (Once again, this is visible in figure 5.10). This different interaction mechanisms between tool and surface, becomes especially evident in the area highlighted with yellow cross hatching. The portion of surface delimited by the yellow rectangle is in fact a recessed indent, added to the design of the cast as a result of a finite element analysis (FEM) to reduce the stress concentrations in the machined part. The left caliper orientation therefore see the tool entering this area at the bottom horizontal edge and exit at the left vertical edge. Vice versa, the right caliper orientation sees the tool entering from the vertical edge and exit from the horizontal. This implies that in the right hand caliper orientation, because of the presence of this indent, the exiting surface is not well supported while the tool's cutting edge enters this area. On the other hand, support is provided to a larger extent by the still uncut longer vertical edge in the left hand caliper orientation, since the cutting edge enters the area from the shorter horizontal edge of the indent. Therefore, the practical implication of this interaction is that the tool's cutting action is facilitated when entering the indented area in the left hand caliper orientation. Conversely, when the cutting edge enters the indent region in the right hand caliper orientation, the axial feed force prevails on the tool's cutting action, causing that portion of the surface to be pushed forward and result in the formation of a thicker and potentially larger disc burr.

This behaviour is easily noticeable in the formation of disc burrs that are presented in figure 5.10 and figure 5.11. It can be observed that there is a distinct difference in how the disc from the left and right hand caliper orientations appear. Specifically, there is a remarkable contrast in how material from the indented area participates or not to the burr formation. A well defined separation of the disc from the indent area occurs at the exit of the respective region in both the left and right orientation. However, because of how the disc is shaped overall, in the burrs from the left hand caliper, the entire section seem to have a tendency to separate from the main body of the disc. Hence, burr formations from the left hand caliper orientation are generally thinner and smaller, and altogether easier to evacuate from the workpiece. Nonetheless, material from the same region of the exit surface remains connected to the discs from the right hand caliper orientation more often than not. Yet, a distinguished separation line remains visible where the cutting edge exits from this region.

Additionally, left and right disc burrs can be set aside for their unlike tendency to curl or fold onto themselves. As illustrated in figure 5.11 the left discs generally have a significantly higher degree of folding as opposed to the much flatter burrs from the right hand caliper. Combined with how they form smaller discs, the thinner and folded burr from the left hand calipers are overall more compact in size than their right hand equivalents.

From a chip evacuation perspective, smaller chips and burrs are to be preferred as large disc formations (such as burrs from the left hand caliper) are more difficult to evacuate. In the eventuality that a larger disc remains trapped in the pocket behind the internal pillar presented in figure 5.4, its removal will consequently be more arduous. Finally, this clarifies the unbalanced distribution of failures in the left and right hand calipers during testing. Moreover, this explains why discs that are harder to evacuate during machining operations have a higher tendency of persisting with the calipers and getting scattered across the manufacturing stations.

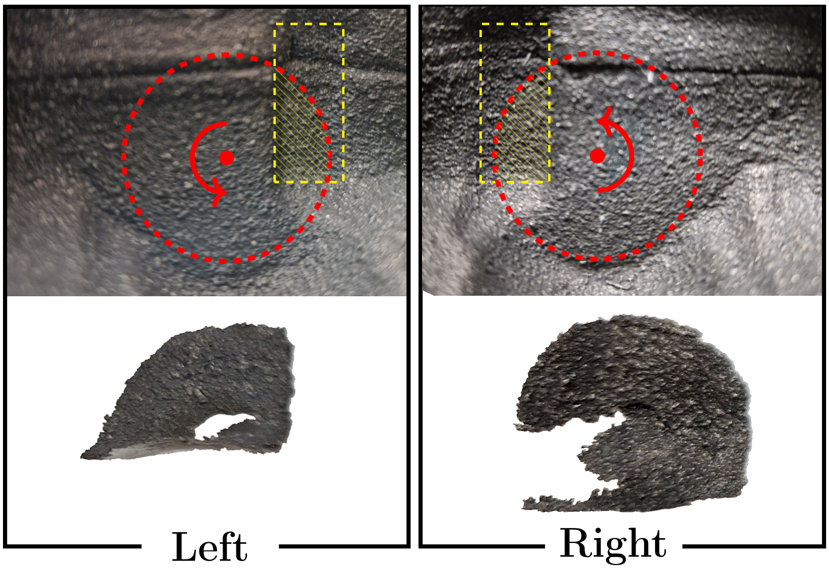


Figure 5.10: Topological characterization of chip formation in the left and right 22" caliper orientations.

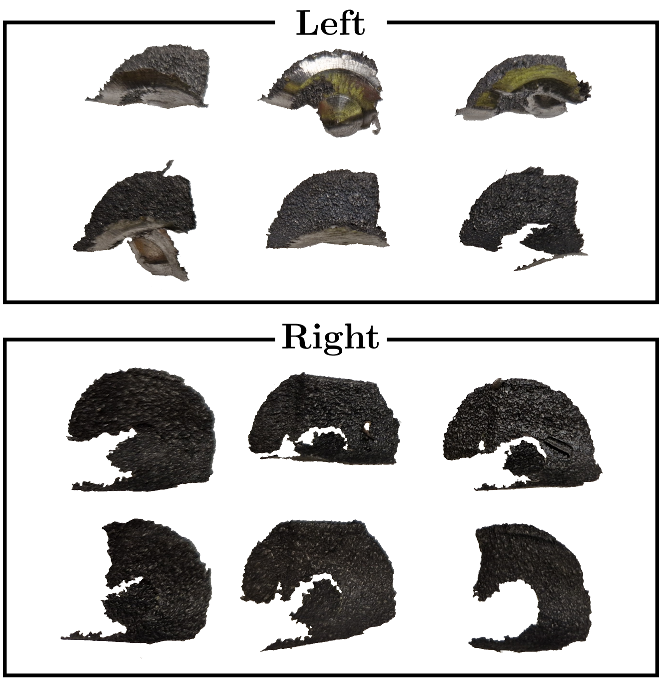


Figure 5.11: Chip formation in the left and right 22" caliper orientations.

In contrast, although not being extensively investigated in this study, there is a smaller brake caliper (The 19 inch model) whose machining process is also responsible for similar disc burrs to the ones found in the 22" calipers; presented in figure 5.12. These discs have shown to be particularly problematic as they are found in a majority of parts exiting the LiCON machine. The disc found in the 19" calipers is particularly flat and intact, which makes for a disc that is significantly more difficult to remove from the internal pocket, especially after being forced there by the jet stream of cutting fluid. This is supported by the gathered data presented in table 4.1 which shows that a large share of discs from the 19" is present at the EDC facility.

The results illuminate a possible correlation between the size of the disc and its respective difficulty of removal; larger discs are harder to remove as they may remain stuck in the pocket between the pillar and the main body of the caliper (This can be seen in figure 5.4). While smaller discs and chips can freely exit this area once flushed with coolant or by effect of a handling sequence, larger disc burrs would have to also be oriented in a particular way which cannot be determined in principle. In practice this means that burrs from the 22" calipers in the left orientation are the easiest to evacuate, followed by the 22" in the right orientation, and the 19" calipers both in the left and right (The disc burrs from the 19" have worse characteristics for chip evacuation). Although there are apparent hints of discs from the 19" caliper having a different topology based on the caliper orientation, this has not been investigated due to the marginal production volume of the 19" caliper in comparison to the 22".

Figure 5.12: Disc burrs from the machining operations of the 19 inch brake caliper model.

From a machine operations perspective, this chip is formed by the combined action of tool T517, which breaches first through the hole's exit surface, and tool T4172 which completes the feature and detaches the disc. An illustration of the machining section with tool T517 as well as a the overlapping action of tool T4172 are presented in figure 5.13.

Mindful of this peculiar sequence, it is possible to investigate what role is played by either of the tools and how a pondered choice of cutting data can contrast the formation of discs (See section 6.4.1 for a complete discussion on cutting data influence).

Another important aspect to this discussion is the fact that all casted blanks come with some dimensional variation that is connected to the casting operations at the foundry. Figure 5.14 illustrates the 3D scan of two different blanks from the foundry. As it can be noticed by the color scale, both samples have variations of up to ±1.5 mm which could potentially affect the formation of chips in the machining operation of feature ②. Given that the so-called *damaged discs* have a thickness ranging from 0.5 to 2 mm, such variations in the casting, combined with the inevitable clamping imprecision when the parts are fixed in the machine, will most likely produce chips of different thicknesses. This issue becomes even more relevant when combined with the fact that the chip itself is formed by two different tools that they take turns halfway through the drilling operation. Additionally, the second tool in this sequence (T4172) is not equipped with cutting inserts capable of performing a cut in the core region of the hole. This means that, if for some dimensional

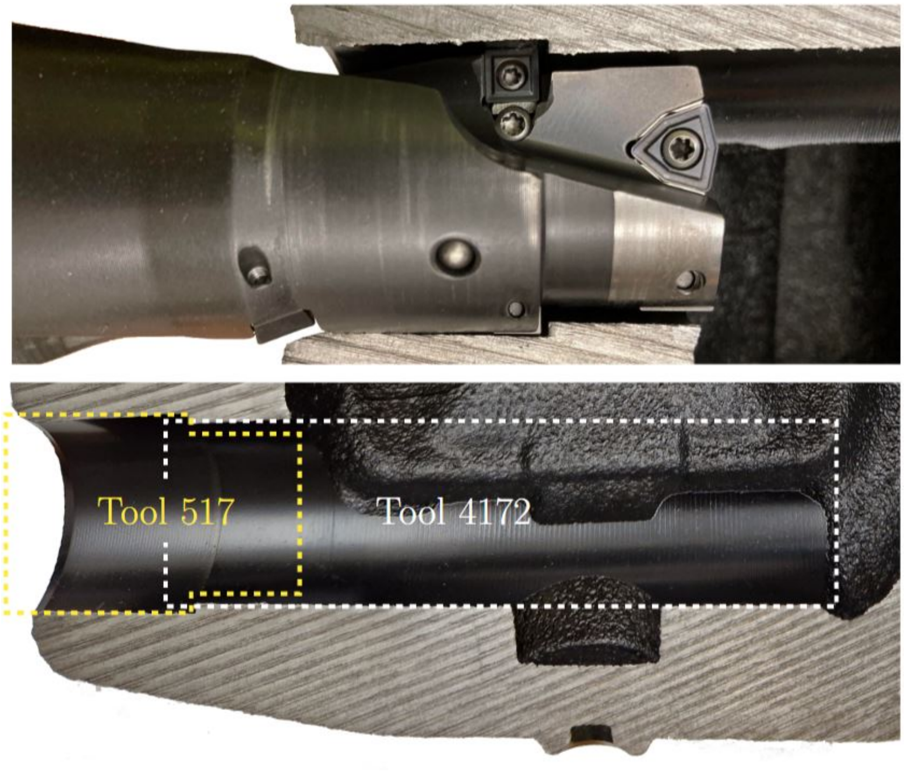


Figure 5.13: Tool T517 (above), utilization of T517 and T4172 in machining of feature ② (below).

variation in the casting, the previous tool (T517) does not breech through the center of the hole, the cutting action of T4172 will be replaced by a purely axial action that favors the formation of the disc rather than a more dissolved chip. Despite the obvious and already known disadvantages that this chip can cause, such a situation may entail a much higher load on the tool and tool holder, and a reduction in tool life. In other words, the tolerances and repeatability constraints that this machining strategy requires in order to operate correctly, are higher than what the intrinsic nature of the process can offer.

In conclusion to this analysis it can be inferred that the topological features of the casting, when interacting with tool T517, contribute to the formation of disc like burrs. This phenomenon occurs in a similar yet different way, depending on the left or right orientation of the casting. While in the left-hand castings the discs are thinner and for the most part folded onto themselves, the right-hand version produces disc that are harder to remove from the machined part. This is believed to be the main factor causing a right-predominant failure distribution in downstream processes, as previously illustrated in figure 4.3.

5.2 Cooling and Lubricating Solutions

During the machining operation, cutting fluids assists the chip evacuation and supply cooling to the cutting edge. Although the presence of this fluid is both needed and in general beneficial, once the operation is concluded and the supply of cutting fluid is interrupted, the thin film of liquid that remains on the surface of the workpiece then begins to dry. This is

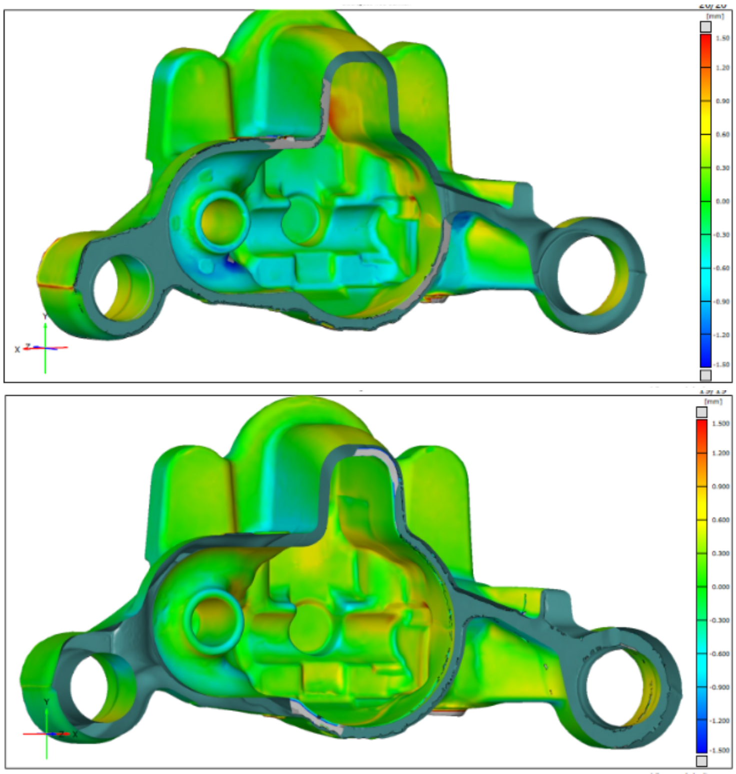


Figure 5.14: Section of 3D scan of the internal geometry as casted.

when the adherence of the metal chips to the workpiece becomes stronger and increasingly problematic. Therefore, it is important that the cutting fluid and/or any chips that may remain on the caliper's surface, are removed before extensive exsiccation has occurred. The bond strength of the dried cutting fluid is in part dictated by the oil content in the emulsion. While oil is essential to lubricate the cutting edge, it can become detrimental for the chip removal if present at too high concentration. Issues such as hydraulic leakage or excessive presence of machine lubricant, might contaminate the coolant medium and increase its oil concentration with negative consequences on chip adhesion.

5.3 Effectiveness of Chip Removal Solutions

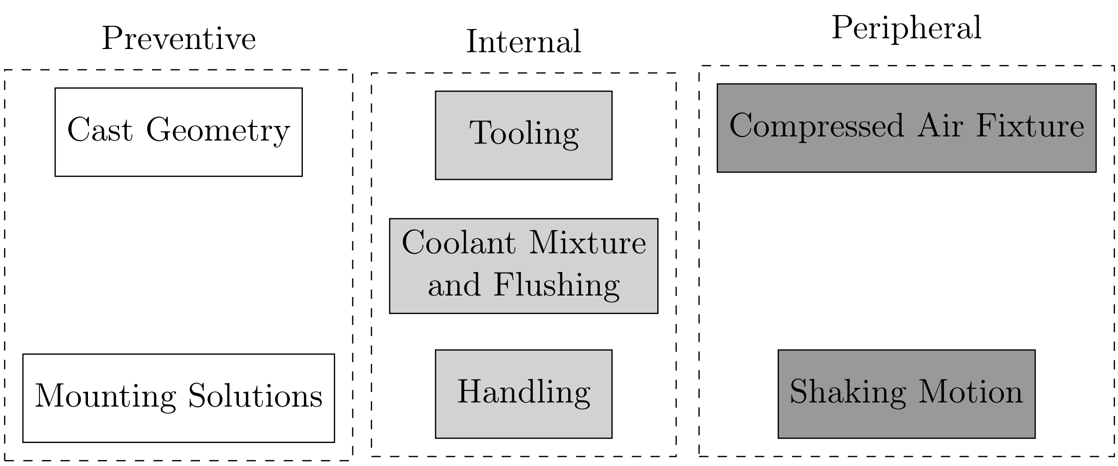


Figure 5.15: Mapping of chip removal interventions.

Current interventions for lowering chip carryover can be divided into three separate categories; preventive, internal and peripheral, depending on the stage at which they can be implemented. Essentially this refers to when in the production flow, this solutions are managing the formation of the chip, how it gets distributed, and eventually removal. This is structured on a left to right basis, meaning that peripheral solutions will not have an effect on internal solutions which in turn do not affect preventive solutions. On the other hand, interventions to the left will affect the performance of interventions to the right.

Preventive solutions can be regarded as the predefined variables that do not play an active role during manufacturing. For instance, the cast geometry has been adapted to minimize the required material removal. Similarly, the mounting solution has an effect on the accumulation of chips around its contact regions. Figure 5.16 presents an image of a caliper that was flipped directly after machining had been finished. The regions where chips have been accumulating are hidden behind pillars that are ensuring a correct mounting position.

Contrary to preventive interventions, internal interventions refer to the active elements during machining of the workpiece; tooling, coolant mixture and flushing, as well as handling movements inside the machine. These factors are the core free parameters dictating the chip formation and direct removal.

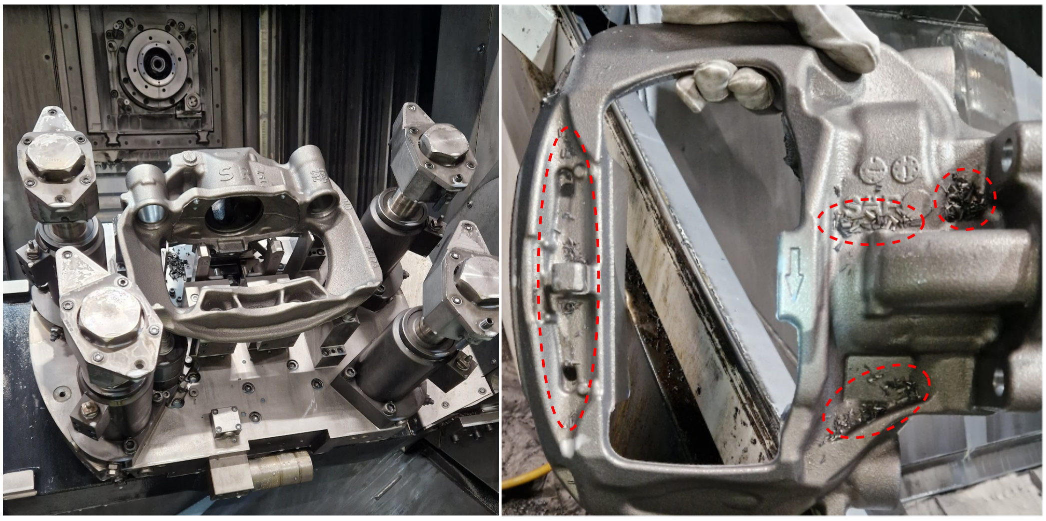


Figure 5.16: Chip accumulation in proximity of fixturing points.

5.3.1 Flushing Sequence

The flushing is performed as the last internal operation of the machining sequence, and it is conducted with the objective of removing remaining chips. As illustrated in figure 5.16, short chips accumulate about the contact points where the workpiece is fastened to the machine table, with minor volumes of chips found elsewhere. Henceforth, the effectiveness of this operation was investigated by inspecting the calipers between the last machining operation and the flushing sequence. A comparison of chip accumulation before and after flushing is presented in figure 5.17 in which the left image represents a caliper before flushing and the right image after flushing. A close inspection on multiple occasions has revealed that there is no noticeable difference on chip volume before and after flushing. Since this operation constitutes 5.54% of the cycle time in the productions bottleneck it highlights the potential benefits of removing it from the machining sequence. This can be performed in line with the theory of SMED (Single Minute Exchange of Die) by allocating chip removal to external interventions such as the robotic arms next to the machine centers, therefore reducing the cycle time in the machine.

Figure 5.17: Effectiveness of flushing operation on machined calipers (Left: no flushing, right: flushed).

5.3.2 Compressed Air Fixture (CAF)

Persistent chips that have not been removed during machining need to be addressed through peripheral systems. This is currently performed in two different ways: utilizing compressed air, and with a robot arm shaking the caliper (Assessed in subsection 5.3.3). The calipers are placed into the first chip removal solution which then utilizes compressed air directly after machining has been finished, with the aim of removing chips and remaining fluids from the surface of the workpiece. While conceptually appropriate and positioned where most needed, the effectiveness of this feature is limited by the fact that the box which hosts the air nozzle is unfavourably small. Additionally, once blown away from the surface of the caliper, chips and fluids are not actively removed from the box and, given its small size, have no place to go and can easily be blown back onto/in the workpiece. The CAF is arguably somewhat effective at removing short chips and coolant on the surface, but does not solve the potential problem of internally persistent chips. The operation at this station takes approximately 25 seconds.

5.3.3 Handling by Robotic Arms

Later in the process, a shaking motion is conducted in order to loosen any persistent chips in the housing of the caliper. This motion is iterated three times at three different angles to account for the different potential pockets that may cause chips to stick around. It was noted however that calipers were positioned in such a way that the only escape route for the internal chips is the narrower of the two openings in the cast design. Whereas the larger opening on the opposite side would potentially provide a more effective exit path for chips that are trapped in the workpiece.

In other words, flipping the caliper around in terms of how it is held during the shaking motion would likely result in a greater amount of chips escaping the housing because of the larger opening and the more favorable geometry of neighboring surfaces. This would however imply that the portion of the caliper that is intended to be placed on the opposite side of the brake disc would risk catching some of these chips as they escape the caliper housing. Nevertheless, this may be easily avoided with an intelligent orientation of the workpiece during the operation of the motion.

A deeper analysis of failures and issues in the downstream processes has highlighted a major difference in failed parts that were machined in different machines and by different spindles. Besides an obvious potential role played by individual machine behaviour (And different wear rates of components across the machines), there is a significant difference in how the machined parts are handled, depending on which spindle the calipers have been machined by. Specifically, the robotic arms adjacent to the machines are capable of grabbing two parts simultaneously. This means that if and when a part is picked up first and re-positioned last, it will face twice the handling motion compared to the other part. The handling sequence of the robotic arms is arbitrary yet affects failure rates of between parts that have been machined on the two spindles. This spindle favoured handling thereby illuminates the effectiveness of handling solutions on the removal of chips stuck in the internal cavity of the caliper.

The strengths and effectiveness of each intervention is indicated by the chip variants and their relative quantity, found to be removed at the different stations. The chip-type summary in figure 3.3 reveals that the two peripheral interventions (CAF and handling by robotic arms) address two different challenges and complement each other.

6 Potential Improvements

Based on the previously reported findings, this section illustrates potential future implementations to address and reduce the magnitude of the problem at hand.

The selection of suggestions that are hereby presented was pondered upon how they would affect the already existing installments and their rigidity in respect to possible changes in the future production scenario. Figure 6.1 presents a prospective relationship between the stability of the production process as a whole, and the extent to which an implementation is affecting the system. For example, solutions that are defined as *internal* to the process would be tailored to the process itself and could therefore, be negatively affected by changes to the product design or by production of different product types. On the other side, *external* solutions are not affected by the process (Machining operations) and would hence have greater flexibility and span of validity. Based on this reasoning, the curve in figure 6.1 represents where implementations are needed most and are most efficient. While *external* solutions are possible and potentially effective for highly stable processes, their use would not be ideal as the same result could be obtained with a specific *internal* solution. Nevertheless, the main take away is that internal solutions must be avoided if the process is unstable as any minor variation would potentially make them useless or even counter productive.

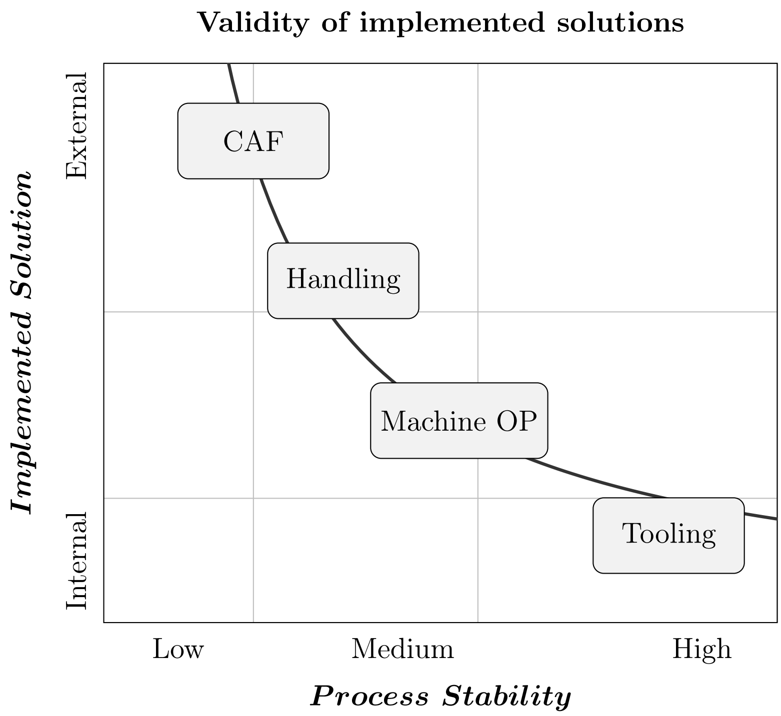


Figure 6.1: Mapping of Possible Solutions.

<u>Generation of hypotheses:</u>

In order to provide a cause-effect association between each of the suggested implementations and the changes that each of them might impart to the current production scenario, it was deemed appropriate to establish a model that would reflect such relationships. The

Hypotheses Relationship Diagram in figure 6.2 represents the logical model implemented to highlight this concept. Nevertheless, it is important to notice that this diagram does not provide a time based or sequence based portrait of the manufacturing flow but on the contrary, it provides the framework to asses each of the possible implementations, with an established set of metrics, that would remain constant and objective throughout the time-span in which potential implementations are carried out. At the center of this diagram, the three diamond shaped nodes do not only represent the three main manufacturing activities, but are also strategical locations where a quantitative assessment of the presence of chips can be performed and recorded over time. The following are the hypotheses generated for this scope:

- **Hypothesis *H1*** - Effect of Cast Design on manufacturing processes.
  - ***H1.a*** Cast Design has a direct effect on the effectiveness of machining in the LiCON cell.
  - ***H1.b*** Cast Design has a direct effect on the assembly procedures.
  - ***H1.c*** Cast Design has a direct influence on operations at the EDC facility.
- **Hypothesis *H2*** - Contributing factors to the Machining manufacturing step.
  - ***H2.a*** The sequence of machine operations in each of the LiCON centers has an influence on the overall performance of the LiCON cell.
  - ***H2.b*** - The choice of tooling in each of the LiCON centers has an influence on the overall performance of the LiCON cell.
- **Hypothesis *H3*** - Effect of external implementations.
  - ***H3.a*** How the machined parts are handled has a direct implication on the operations conducted in the EDC coating facility.
  - ***H3.b*** How the machined parts are addressed by the compressed air fixtures (CAF) has a direct implication on the operations conducted in the EDC coating facility.
- **Hypothesis: *H4*** - Effect on downstream processes.

Additional hypotheses could be drawn across the external/internal implementations and different manufacturing stages. These are indicated via dashed lines, and indicate the indirect effect that each of the items may have on the final assembly of the product. These hypotheses are not directly tested but their validity can be inferred based on the results provided by the other hypotheses, given that the sequence of manufacturing stages is left unchanged. Among all hypotheses, hypothesis *H1.b* eludes marginally from the focus and scope of this thesis project, and will therefore be ignored. While it is quite self explanatory that the cast design will most definitely affect how the final assembly comes together, this does not directly correlate to the carryover phenomenon (Section 1.2) and the formation of chips.

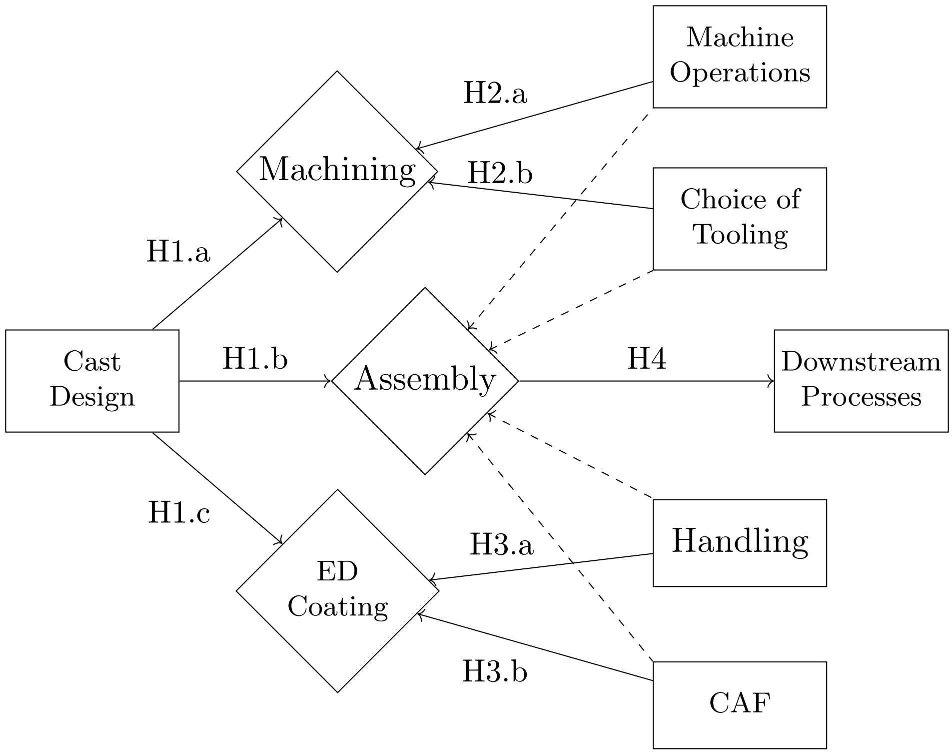


Figure 6.2: Hypotheses Relationship Diagram for testing of the Potential Improvements.

Finally, another aspect to be considered when developing and implementing solutions, is the already established flow of activities and organization of tasks at this site. Each of the presented solutions, thoroughly described in the following subsections, is naturally subject to the context in which its implementation would take place. Of greatest importance is how changes would affect an actively running production system. As such, existing physical and economical limitations cannot be overruled, but must be at all times embraced in preparation to any intervention. Although not universally relevant, it played a significant role in the scheduling of potential implementations in the time scope of this study, as some tasks required a longer execution time than what was available.

6.1 Cast Design

While being strictly bound to external constraints in the design product requirements, adaptations to the cast design offer a large range of possibilities to solve the disc burr formation at its root; that is, the interaction of the tool with the workpiece. Although, any intervention on the cast would provide variations in the phenomenon behaviour that would affect all of the other solutions mentioned in this section and figure 6.1. A successful future development of the cast design would in theory be preventative and therefore overrule the need for any other implementation. Despite the high cost and time requirements for a design review, cast design is considered of great interest for its high potential of addressing the problem at the source, once and for all, with a one-time investment. This section addresses the cast design and how findings from literature (Section 2), previous experience at the company, and experimental results can be combined and applied for the development of a better cast geometry.

As previously mentioned, the most problematic chip regarding caliper quality exchange (Number of failures per total production) is the damaged disc which is formed during the machining of feature ② in figure 5.1. Henceforth, one of the proposed changes would be to alter the exiting surface in relation to how the hole is performed, in a manner that would allow the chip to form in a functional way to its asportation. The main idea behind this would be to create a geometry that can support the exit surface until the hole is fully machined. This way, instead of the surface yielding and forming a burr, the material would be removed in the form of small chips for the entirety of the hole. One way of doing so is by changing the angle of the exiting surface from perpendicular to the drilling direction, to a slightly slanted exit surface. Figure 2.7 illustrates the perpendicular exit to the left and the slight tilt of the exit surface to the right. If the slope is not sufficiently steep however, this adaptation might cause the originally completely circular discs to only be formed partially without fully addressing the issue. In this case, there is a possibility that the significantly more rugged discs which are prone to persist inside the caliper, might result more problematic than the initial scenario. On the other hand, with an appropriate slope of the exit surface, the disc like burr could roll on itself during its very formation, and this way, result in a thin, more compact, and overall easier to remove chip.

Furthermore, additionally to the presence of a slanted exit surface, it is of interest to analyze how other surface geometries might influence the formation of burrs. Figure 6.3 present a possible sample specimen that could be used for drilling experiments in a testing scenario. All surfaces have been inspired by theoretical background and details of the current cast design, and have in common the presence of a draft angle to allow this features to be casted. While a concave surface is believed to offer more support to the disc during the final moments of the drilling operation, the slope with a slot and the slope with a split in figure 6.3 are aimed to break the disc burrs into smaller parts for easier chip evacuation.

Another change in the cast design that could be considered is the adaptation of the pocket, visible in figure 5.4 and figure 3.2, to a closed off area that would not accommodate the possibility of large disc burrs and chips getting stuck between the pillar and the main body of the caliper. That being said, the current design of this feature was the result of a long structural and weight optimization process that would be good to preserve in the future iterations. Finally, especially given the following manufacturing process at the EDC facility, any newly suggested cast design improvements should be mindful of how this operation is performed. In particular, since the machined parts are submerged in a sequence of chemical baths, there is a risk for air bubbles to form in proximity of certain features and therefore preventing a correct coating of the part. Hence, aware of this aspect, cast design should avoid such features as much as possible.

6.2 Compressed Air Interventions

This section addresses all possible implementations regarding fixtures that utilize compressed air to clean the workpieces from chips and fluids that persist after machining

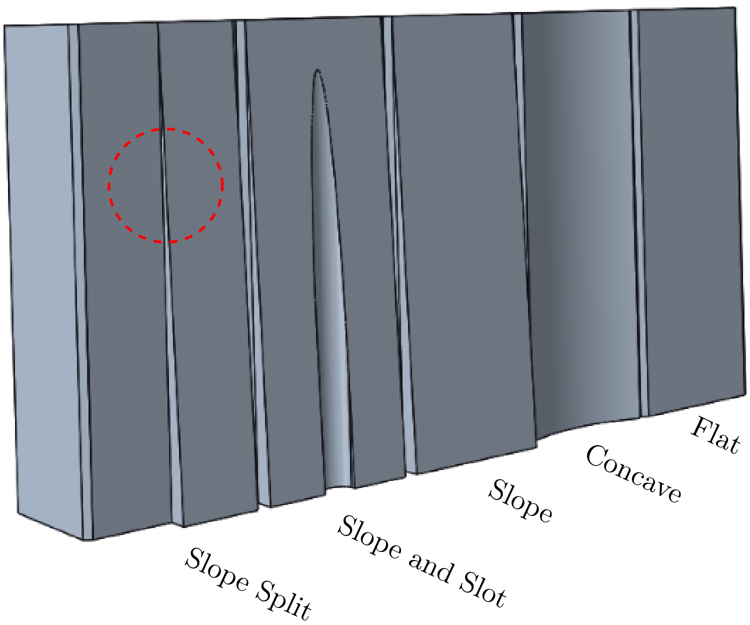


Figure 6.3: Sample specimen for testing of exit surfaces for feature ②.

operations are concluded.

6.2.1 Adaptation of Current CAF Solutions

There are multiple potential adaptations that are of interest regarding the current installment of the boxes with compressed air nozzles; figure 3.9 (Left). The main weakness of this implementation is its inability to reach the damaged or rugged discs that persist inside the caliper housing. The nozzles which are currently positioned relatively distant from the caliper, do not reach the inside geometry and the way this fixture was designed does not provide a way for discarding the chips that have been removed from the calipers. This solution currently requires to be regularly cleaned by an operator with the aid of a vacuum cleaner. It is also possible that by the action of compressed air, some of these chips that remain in the box get pushed back in/on the caliper. Such re-circulation of chips inside the box could be addressed by creating an escape route or simply increasing the height of the box. Furthermore, the high flow and low pressure of these nozzles fails to effectively address areas of chip accumulation. While current solutions might have a positive influence on chip removal, this is far distant from being effective; fluid and chips are to some extent still present after cleaning in these fixtures.

Another option would be to reevaluate the generic CAF solution altogether by combining the air nozzles and the robotic arm. Similarly to the specialized CAF in figure 3.9 (Right) used on calipers before entering the measuring station, a larger apparatus could be installed in proximity of the larger robotic arm by the exit of the LiCON cell. By doing so, the shaking motion of the robotic arm could be paired with the benefits of carefully oriented air nozzles. A very crude graphic representation can be observed in figure 6.4, where the machined caliper is rotated in a stream of compressed air nozzles, directed to optimize the removal of persistent chips.

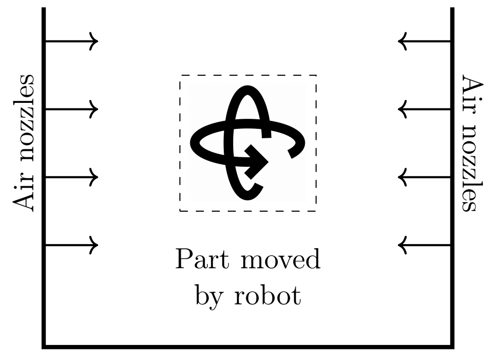


Figure 6.4: Schematic representation of CAF with robotic arm access; section view.

Given the current overcapacity of the robotic arms this should be a feasible installment that would not affect the throughput time; therefore, the productivity of the LiCON cell would not be affected. The construction of this apparatus would require a large container such as a large section of ducting/tube, similar air nozzles to the ones visible in figure 3.9, and reprogramming of the adjacent automation systems. Because of the large footprint required by this solution, it would not be placed by each LiCON machines but it would have to be positioned centrally in the cell. Therefore, persisting chips would be addressed at a later time and could still be present along the conveyor belt and on carriers before reaching this cleaning solution. For this reason, a solution that addresses the presence of persistent chips immediately after the machining operation is completed, and as close as possible to each of the machine centers, is to be preferred.

6.2.2 Carrier Cleaner

Another current issue that was identified as consequence of the chip carryover phenomenon (As conceptually illustrated in figure 4.1) is excessive wear on the conveyor belt that spans across the LiCON cell. The large volume of chips that are carried over from the machining operations can result on the pallet carriers that run on the conveyor belt, and more importantly on the conveyor itself. Smaller chips can then find their way between the moving parts of the conveyor and score/abrade them by increased friction, to the point the belt might potentially fail (and has failed in the past). Attributing a section of the conveyor for automatic carrier cleaning could hence prove beneficial and reduce the tasks the operators are required to perform, as well as reducing the downtime needed to perform such operations. Essentially, this solution would utilize air nozzles positioned on one side of the conveyor to direct chips into a collection box placed on the other, as schematically illustrated in figure 6.5. This way, leading to less chips in circulation, causing less wear on the conveyor and other peripheral systems.

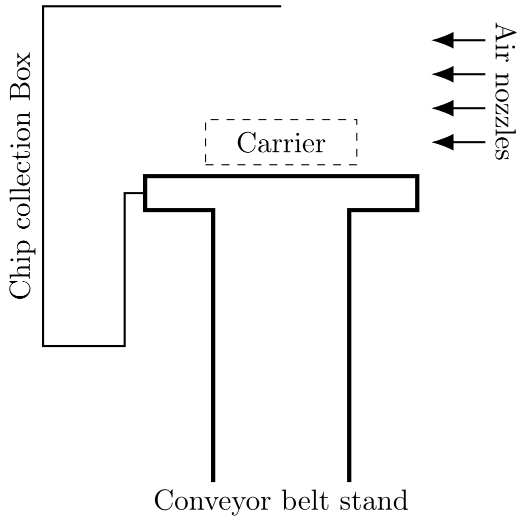


Figure 6.5: Schematic representation of CAF for carrier cleaning; section view.

6.3 Handling of the Workpiece

The workpiece undertakes numerous handling operations by the action of automated robotic arms, at different locations throughout the manufacturing sequence. In this subsection, handling operations within the LiCON cell are addressed and specific improvements are proposed to help minimize the carryover of chips from machining. Handling inside the LiCON machine centers is more thoroughly addressed in section 6.4.3.

6.3.1 Robotic Arm in the Cell

At the moment, the central robotic arm responsible for loading pallets with the machined parts is also programmed to perform a shaking motion (Described in section 3.4.3).Changing the movements of the robotic arm is perhaps the adaptation that will make the fastest acting change in quality exchange since it already is the most successful intervention for removal of the problematic damaged disc burrs. Nevertheless, there are improvements to be made, particularly regarding how the caliper is held during these movements. Currently, the chips are forced through a narrow hole that is marginally larger than the disc itself while the opposite side of the workpiece features a significantly larger escape route. Therefore, if the part was to be held in the opposite orientation, such shaking motion could result much more effective. The sequence could potentially be improved if the caliper is shook to loosen the disc from the corner in the pocket behind the pillar (As visible in figure 5.4), followed by a rotation of the caliper such that the disc is guided by the rear wall of the internal housing, and finally escape from the inside geometry of the workpiece. This movement should be repeated in both rotational directions in order to address chips potentially stuck in both the left and right orientation of the caliper.

Additionally, the possible implementation of the improved compressed air chip removal solution proposed in section 6.2, figure 6.4, would require capacity from this same robotic arm. Hence, this operation could become part of a shaking motion which would happen under the effect of the compressed air nozzles in the improved solution. This way, the beneficial effect imparted my the movement of the workpiece via the robotic arm, would be complementing the cleaning effect of the compressed air nozzles. Even more so, this solution would allow for a more precise and adaptable cleaning sequence, and access to all the chip accumulation areas.

6.3.2 By Robotic Arms Nearby the Machine Centers

The handling of the workpieces by action of the robotic arms adjacent to the machine centers, provides another opportunity to remove chips and cutting fluids from the machined calipers. This location is of particular interest given its close proximity to the machine centers. Performing chip removal operations at this earlier stage has the major benefit of avoiding chips and fluids to get carried along to the conveyor belt and around the LiCON cell. Therefore, reducing and potentially avoiding the risk of chips contributing to higher wear of the handling system and general contamination of the cell. At this time, the robotic arms in question, not only have almost one cycle (Approximately 9 minutes) worth of waiting time in which they do not perform any operation, but also have a grabbing tool capable of picking up two parts simultaneously. This grabbing fixture features two independent clamping mechanisms that have allowed to optimize the duration of loading and unloading of machined parts and casted blanks in and to the LiCON centers. Moreover, it is believed that this motion could be combined to a shaking motion similar to what described in section 6.3.1, by also integrating the effect of a reviewed CAF, to maximize the cleaning action. Additionally, adapting the motion to overcome eventual differences in how machined parts from different machine spindles are handled (As described in section 5.3.3) should, without any doubt, contribute to isolate and address the chip carryover phenomenon.

6.4 Machine Operations

In this section, aspects that are directly related to the operations performed inside each LiCON machine are addressed. Particularly interesting are aspects such as the sequence of operations about which, any improvement could result extremely beneficial and can be implemented with relative ease. Although this section provides a full overview on machine operations, the choice of tooling utilized in the machining centers will be addressed separately in section 6.5.

6.4.1 Cutting Data

Cutting data is of central importance in determining the performance of the metal cutting process; not only does it directly correlate to tool life and surface finish on the workpiece, but it is also a major factor in how the chip formation occurs. In the pursue of this study to develop improved machining strategies to reduce (or resolve the chip carryover phenomenon), cutting data is addressed primarily from a chip formation perspective, mindful of implications on other aspects of production. The drilling operation involved in the machining of feature ④ in figure 5.1, is responsible for the formation of long helical chips as those illustrated in figure 3.11. Because of the size and elasticity of this chip formation, the removal of these type of chips might result arduous; furthermore, it is common practice to avoid the formation of such chips when possible. From a theoretical standpoint, cutting data can be optimized in numerous ways to address this inconvenient chip type. While not the main cause of rejected parts that fail the functionality test prior to assembly, long helical chips are the only ones, together with damaged discs, that make it all the way through ED coating and over to other downstream processes.

Traditionally, long chips are taken care of via *peck drilling*; that is, occasionally interrupting the feed to allow the chip to break before resuming with the drilling motion. However, given the more complex motion, not only this results in a non desirable increased DOO but it also commonly entails lower tool life, given the additional engaging-disengaging of the tool in the workpiece. An alternative to this rudimentary solution could be to take advantage of the chip breaking principles discussed in section 2.1.3. On this premise, the theoretical chip thickness h_1 can be increased by providing a higher feed rate f. Although this would increase the tendency of chip breakage (As qualitatively illustrated in figure 2.4), if the new cutting data happens to be outside the optimal working range for the given tool, it could also imply greater tool wear and worse surface finish. Finally, investigating the feasibility of converting the conventional *two-fluted* drilling tool into a mill with inserts could be an interesting approach as this solution would in theory allow to adjust a greater number of parameters and a generally better performance. Thereby, various chip breaker geometries and cutting data parameters can be tweaked to increase the performance in DOO, chip breaking, and tool life.

As previously mentioned, the formation of the problematic disc burrs is specifically bound to the action of tools T517 and T4172. As this formation sees a contribution of two tools, pinpointing a solution by only adjusting the cutting data for one of the tools could prove difficult; therefore, some assumptions should be made. In a first instance, if the hole was drilled by tool T517 in its entirety, the axial feed motion could be reduced to lower values for the very last segment of the travelled path. This way the axial force that is normally set to cause the disc burrs to detach from the workpiece, would be minimized, allowing for a more complete cutting operation, even at the very end of the drilling motion. Secondly, if the first assumption could not be met in practice, it is imperative to ensure that T517 breaches the surface to a point where the center of the disc is either cut or otherwise detached from the exiting surface of the workpiece. As T4172 is only equipped with peripheral cutting inserts, failing to do so would imply a direct axial action which would increase the tendency of burr formation rather than complete cutting action. Nevertheless, it is theoretically supported that a reduction of the feed rate (in the limits of the good machinability region illustrated in figure 2.4, where h_1 is greater than h_{1min}) can result in a reduced tendency of tool exit burrs.

6.4.2 Cooling and Flushing

The employment of cooling and flushing actions could also become an effective way of dealing with persistent chips. Nevertheless, while it is easy to introduce a flushing operation, it should also be considered that this comes at the expense of a longer cycle time. Hence, the question: “How much is the chip carryover phenomenon worth? and how much is the company willing to pay to address it?”. In either case and as previously discussed, the currently implemented flushing solutions not only take up a large share of the cycle time but are clearly not able to address the issue. Therefore, this section aims to provide a fresh perspective on the phenomenon and propose new solutions that would exploit the flushing mechanisms more efficiently.

On the one side, issues with the persistent presence of long helical chip could potentially be addressed by experimenting with high pressure cooling to increase chip breakage and chip breaking frequency, as presented in section 2.3 of section 2, Theoretical Background. Nevertheless, such expedient of theoretical principles should be carefully evaluated from a practical point of view before attempting to put it into practice as its implementation might not be so simple. One of the issues being that the cutting fluid pump currently present in the machine might not be sufficient for the supply of coolant at the required pressure. In that case, it might be interesting to evaluate whether to install a pump able to supply coolant at the desired pressure, or if such change is not worth the results. Apart from potentially resulting in better chip breaking this would also likely increase the possible machining speed and therefore, also reduce the cycle time.

Figure 6.6: Spray pattern of internally cooled tool (which could be used for flushing).

Conversely, great focus and effort has been allocated to the development of the machining, which as previously illustrated, contemplates the presence of a rather long flushing operation at the end of the cycle 3.7. The implementation of this detail has been carried out to address the chip carryover phenomenon and as an attempt to reduce its incidence on failures in testing. While having a relatively marginal effect on the small chips which accumulate on the outside surfaces of the workpiece, this feature fails to address the more problematic types of chips that remain stuck in the inside geometries of the brake caliper. Additionally, while not removing all chips from the workpiece, this sequence adds to the volume of fluids that remain in the machined part and end up dripping on the floor, or worse, on handling equipment. Moreover, the flushing head used to perform this operation requires a tool change that implies additional cycle time.

While the specific flushing heads have the ability to provide high volumes of coolant with a precise direction, it is also true that some of the tools have the possibility of being internally cooled and could hence deliver pressurized fluid to target chip accumulation areas (Illustration in figure 6.6). If such feature was to be employed utilizing the tool for the final operation(s) the need for a flushing sequence with a dedicated and specific tool might not be relevant anymore. The cost-benefit for this operation should be re-considered as the long time it requires would likely be more valuable in terms of increased manufacturing capacity. The overall recommendation is therefore to focus on ways of addressing the chip carryover problem so to reduce the cycle time in the LiCON machine center (Which is the bottleneck of the current production organization). In other words, instead of performing a flushing sequence with the hope to remedy the issue, the phenomenon should be addressed at its roots. If this is not possible, peripheral methods that do not constitute a burden on the cycle time inside the machine, should otherwise be implemented.

6.4.3 Machining Sequence

As already mentioned in multiple occasions, the most problematic chip type is the partially formed discs which get easily stuck in the inside geometry of the brake caliper. The now problematic operation is performed at the end of the sequence but could be anticipated in the sequence so to take advantage of the clearing action of the high pressure coolant used in the following machining of adjacent features. There are at least two operations of adjacent features, whose tools have channels for high pressure internal cooling which could provide an efficient flushing effect. Taking advantage of this possibility would not only minimize the need for a dedicated flushing sequence, but also reduce the cycle time and number of tools that need to be stored in the machine's magazine.

Upon an inspection of the calipers prior to the flushing sequence, with a different sequence of operations in which the final operation was machining of feature ④ (Not presented in table 6.1; based on the old sequence, with T508 and T409 last), it was noticed a minor accumulation of fine chips/shavings produced by the reamer which is presented in figure 6.7. While being relatively small, this accumulation of material in the inside geometry of the workpiece is unsightly and has no reason of being there if it can be otherwise removed. Therefore, the *New Sequence* of operations illustrated in table 6.1 presents a similar structure with the main difference being that the final operations are performed by T449 and T404 instead of T508 and T409. By doing so, if any shavings from a reamer should accumulate in the workpiece, it would be chips from the smaller T404 (⌀9 mm reamer) rather than from the larger T409 (⌀25 mm reamer). While a complete removal of reamer shavings is unlikely for reaming tools that are not internally cooled such as the ones currently adopted, this new sequence minimizes the potential for it becoming a problem. Finally, it must be reminded that this proposal is based on the idea that the

*The description refers to the operation performed by the tool specified in the *Old Sequence*.

New Sequence	Old Sequence	Description *
T500	T500	Milling operation 1
T455	T455	Drilling operation 1
T460	T460	Operation 2
T450	T450	Operation 3
T407	T407	Milling operation 2
T501	T501	Drilling operation 2
T521	T521	Milling operation 3
T410	T410	Drilling operation 3
T416	T416	Milling operation 4
T413	T508	Predrill hole 1
T451	T409	Ream hole 1
T461	T449	Predrill hole 2
T420	T404	Ream hole 2
T517	T413	Operation 4
T4173	T451	Operation 5
T4192	T461	Operation 6
T508	T420	Milling operation 5
T409	T517	Drilling operation 4
T449	T4173	Predrill hole 3
T404	T4192	Ream hole 3
–	T422	Flushing operation

Table 6.1: Proposal for new sequence of operations.

time currently employed for flushing operations inside of the machine, would be best used to increase the capacity of the cell. Furthermore, this new sequence does not aim to be a universal solution to the problem, but an instrumental step in the right direction for future developments, and the precursor for a study on cycle time optimization.

6.5 Choice of Tooling

Choice of tooling is an aspect that closely relates to machining operations and the changes proposed in section 6.4. While choice of tooling has not been a focus of this project, it is now clear that it cannot be left out of the equation as so many other considerations depend on what type of tool is used for a particular operation, how much it costs, and what cutting data can be utilized, only to mention a few. Therefore, assuming tooling as constant would also not be the correct approach, as tooling is continuously being developed by suppliers, re-assessed by specialists at the company, and changing based on what offers the best cost/performance compromise at any given time. Hence, a better approach to tooling in the broad field of study that this paper offers, is to consider tools as variables within certain boundaries, or as a field that can only assume a predetermined set of values. To provide a practical example, T404 should not be referred to utilizing its specific part code from the supplier, but more generally as a sintered carbide reamer with no internal cooling, able to operate between certain limits of feed and cutting velocity, utilized to machine a particular feature. This way, if the tool was to be replaced with a similar one, the same considerations could generally apply or be adapted to it. The machining of feature ④ in figure 5.1 offers a good example on why it is important to be mindful of tooling when suggesting possible

Figure 6.7: Internally remaining chips prior to flushing when ending machining with feature ④ (Drilling and reaming).

implementations. Currently this operation is performed by a two flute solid drill which is responsible for producing the long helical chips in figure 3.11, known to be somewhat problematic.

A possible solution discussed in section 6.4.1 was to increase the feed rate f. However, practical experience has shown that these drills are limited in feed rate as higher values can cause vibrations at eigenfrequencies and consequent instant tool failure. In this case, having knowledge of this limit has enabled the formulation of other possible implementations (also discussed in section 6.4.1) or the need for a new type of tool. Transitioning from the current two-flute to a more stable three-flute drill could henceforth be of interest to make operations more efficient, as well as potentially allowing a higher feed rate for better chip breaking and shorter DOO. Similarly, in regards to other aspects such as the diameter of the flushing canals in the tool and the possibility of adapting *ad hoc* strategies, have been discussed in section 6.4.2. For the same feature again (Feature ④ in figure 5.1), the transition towards an insert drill with an integrated reamer is already under discussion. This change will supposedly have the benefit of a prolonged tool life, and accommodate easier maintenance due to the replaceable wear parts rather than having to be manually sharpened on a grinding wheel, as well as shorter operational time given its 2-in-1 action. An example of an integrated reaming and drilling tool can be seen in figure 6.8.

Following the choice of tooling, the choice of inserts can be seen as another interesting aspect. This differs from the choice of tooling itself as the same tool can be equipped with different inserts and therefore, present disparate micro geometries (which would behave in different ways). Particularly the micro-geometry of chip breakers and edge radii r_β, are interesting parameters while looking to improve the machining operations of features which produce problematic chip formations. For instance, edge radius can be altered to facilitate the tendency to leave behind a clean exit and formation of complete disc burrs, if this is the desired strategy. This way, avoiding the detrimental partially formed discs which tend to get stuck far more easily than a fully formed, smooth edged, disc burr. This could be of close interest for feature ② where burrs are formed into the shape of damaged discs. This being said, as edge radius is not the only parameter into play, a sharp geometry would likely be subject to high wear during the intermittent portion of the operation, once the disc formation is initiated.

Figure 6.8: Example of an integrated drilling and reaming tool.

7 Experimental Results and Discussion

This section addresses how the potential improvements that were suggested in section 6, have been implemented on site, and how the production context has responded to such changes. The complex nature of the chip carryover phenomenon calls for a thorough evaluation over a broad manufacturing context; for this reason, the assessment methods that were establish to evaluate the effect of potential improvements include a rigid framework based on hypothesis formulation and verification, as well as a more flexible, observation-based, approach.

Following the hypothesis generation in section 6 and based on the Hypotheses Relationship Diagram in figure 6.2, the following verification methods can be established for each of the statements. The methods hereby presented rely primarily on quantitative metrics assessed at the EDC facility (Section 7.1) and during testing at a later manufacturing stage (Section 7.2). This way, the hypotheses can be assessed on a indisputable yes/no basis; minor of any systematic mistakes that could have occurred. Nevertheless, because of the convoluted nature of the circumstances in which the chip carryover phenomenon occurs, and in an attempt to clarify and reduce possible bias or correlation problems, each of the hypotheses is also evaluated from a less strict, qualitative perspective. Section 7.3 presents a solution-based evaluation of the Potential Improvements previously illustrated in section 6 while section 7.6 provides some general conclusions about each of the hypotheses.

<u>Hypothesis Verification Methods:</u>

- ***H1*** - Effect of Cast Design on manufacturing processes.
  - ***H1.a****: Cast Design has a direct effect on the effectiveness of machining in the LiCON cell.* This hypothesis is verified if following a change in the cast the design, either of these conditions is verified: the cycle time is reduced, machining in the LiCON cell is otherwise improved.
  - ***H1.b****: Cast Design has a direct effect on the assembly procedures.* As previously mentioned, this hypothesis can, for the scope of this project, only be discussed from a qualitative perspective. No metrics were established.
  - ***H1.c****: Cast Design has a direct influence on operations at the EDC facility.* This hypothesis is verified if following a change in the cast design, either of these conditions is verified: the amount of disc burrs at the EDC facility is reduced, the risk of trapping air bubbles during the coating operations is reduced.
- ***H2*** - Contributing factors to the Machining manufacturing step.
  - ***H2.a****: The sequence of machine operations in each of the LiCON centers has an influence on the overall performance of the LiCON cell.* This hypothesis is verified if by changing the sequence of operation the LiCON machines, either of this conditions is verified: the cycle time is reduced, internal flushing operations

are no longer needed, the presence of persistent chips in the caliper housing is reduced, machining in the LiCON cell is otherwise improved.

- ***H2.b****: The choice of tooling in each of the LiCON centers has an influence on the overall performance of the LiCON cell.* This hypothesis is verified if following a change in the choice of tooling, either of these conditions is verified: the cycle time is reduced, internal flushing operations are no longer needed, the presence of persistent chips in the caliper housing is reduced, machining in the LiCON cell is otherwise improved.

- ***H3*** - Effect of external implementations.
  - ***H3.a****: How the machined parts are handled has a direct implication on the operations conducted in the EDC coating facility.* This hypothesis is verified if following changes in the handling of operations of the machined parts, either of these conditions is verified: the volume of chips recorded at the EDC facility is reduced, the presence of disc like burrs is less frequent, fewer issues in the downstream processes.
  - ***H3.b****: How the machined parts are addressed by the compressed air fixtures (CAF) has a direct implication on the operations conducted in the EDC coating facility.* This hypothesis is verified if following by improving the design of the compressed air fixtures (CAF), either of these conditions is verified: the volume of chips recorded at the EDC facility is reduced, the presence of disc like burrs is less frequent, fewer issues in the downstream processes, fewer chips are present across the production floor.

- ***H4*** - Effect on downstream processes.
  This hypothesis is verified if by the verification of *H1-H3*, fewer problems are encountered after the parts have been coated at the EDC facility.

7.1 Chip Presence at the EDC Facility

As already mentioned and illustrated in figure 3.3, the EDC facility naturally constitutes a collection point for many of the chip types. This location is in fact a manufacturing step where all parts produced on site converge and are handled by three different robotic arms (Two while entering the station and one when exiting); moreover, the coating operation involves a significant amount of movement which, if nothing else, could contribute the removal of chips that may be trapped in the inner geometries of the brake calipers. This location is also easily accessible during planned downtime, and planned weekly cleanings allow for a regularly scheduled collection of chips that are carried over to this station.

Figure 7.1 illustrates the data that was continuously sampled at the EDC facility together with a time sequence of the implemented solutions and the share of the total throughput that is connected to parts machined in the LiCON cell. Therefore, this image portrays a direct correlation between implemented changes and their effect on the chip carryover phenomenon, and therefore provides an established metric for assessment. It is important to note that the production of calipers managed in the EDC station is divided with other machining centers; in total approximately 58% of the coated calipers has been machined in the LiCON cell. This allocation will consequently be reflected in the effect that potential improvements have on the chips at the EDC facility. In other words, this means that by only intervening on the LiCON cell, it will not be possible to dismiss all chips carried over to this station. From a theoretical standpoint, only a share of the chips corresponding to the production volumes ratios per different production cell, can be addressed. These ideal limits are inserted in figure 7.1 in the form of red horizontal lines, of corresponding character to the measured source, in order to visualize the theoretical maximum level of improvement that can be obtained by only acting on the LiCON cell.

The first implementation, consisting of a revised handling motion for the robot in the central position of the LiCON cell, took place during week six; therefore, this week should be considered as a transition week. Furthermore, given that the production is organized in batches and there is a buffer storage in between manufacturing operations, the effect of any change in the LiCON cell is not visible immediately at the EDC facility, but gradually and over a period of time. Section 7.3 will reflect upon each and every implemented solution, singularly and with greater detail.

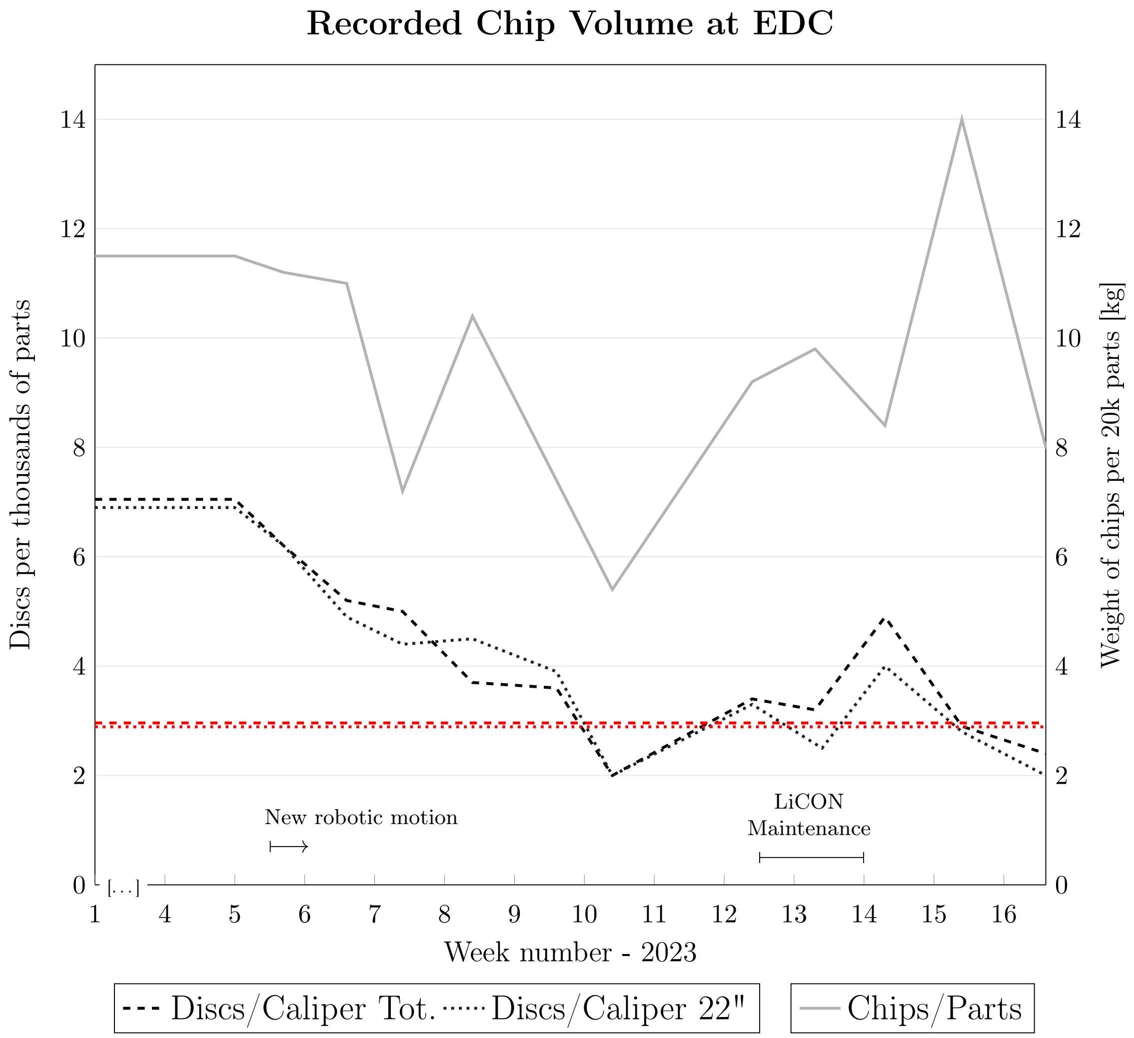


Figure 7.1: Presence of chips at the EDC facility.

Possible flaws to the data presented in figure 7.1 can be linked to the presence of unidentified contributors. While general trends are obvious and unambiguous, showing how major implementations affect the presence of chips and disc burrs at the EDC facility, aspects such as unrecorded interventions on individual machines in the LiCON cell may have marginally affected the progression of the data collected. Additionally, the introduction of a 6^{th} LiCON milling center during the time of investigation, may have also contributed to volatility in the acquired data. Nevertheless, the results from this study have been presented in a conservative way that should not reflect these marginal variations. Most remarkably among all recorded events, the LiCON cell has undertaken some extensive maintenance operations requiring downtime (Including but not only, the replacement of spindles in the LiCON milling centers), which in turn have caused the overall production to be more predominately handled by the Heller line. As new chip removal implemented have not yet been addressed for Heller machines, this would justify a slight increase in the number of disc burrs per produced part, machined during weeks 12-13. Given the presence of a buffering storage between machining and ED coating, the effect of this maintenance is visible in week 14, with about 10 days delay from when the LiCON cell was first affected by the downtime of machines 2 and 3. During this time, the LiCON cell has seen a reduction of approximately 22% for the production of 22" calipers (compared to standard production volumes). Note that this figure was calculated accounting for the fact that LiCON 5 is dedicated to the production of 22" calipers during only 50% of the available machine time (The remaining time is dedicated to the machining of 19" calipers). Transferred to the EDC station, this would imply an expected increase of 12.9% in the volume of discs per 22" calipers, coated at EDC. Comparing week 14 with data prior to maintenance (week 12), there is a 12.1% increase in the number of discs per 22" caliper, between week 12 and 14. This conforms very closely with the initial prediction; the resulting deviation in the volumes presented in figure 7.1 is fully accounted for.

Nevertheless, sampling during week 16 shows that in fact, the presence of discs and chips is stable, oscillating about the minimum theoretical values. During the last 6 weeks that were recorded, disc count per total produced caliper has been reduced by 44.5% (compared to values in the initial sampling) and by 60% for the 22" caliper specifically. Compared to the theoretical minimum for the LiCON cell (as previously calculated, based on the overall volume of produced calipers in 2022), there has been a reduction of 94.2% in the count of disc burrs per all calipers produced by the LiCON cell. For the 22 inch caliper exclusively, the reduction has been 3% greater than what was theoretically expected. In practice however, these ratios are subject to the weekly variations in the produced volumes, as well as any variation to the share of parts machined by LiCON or Heller respectively. Given the recent trends in transitioning machining operations for the 22" calipers from the older Heller line to the new LiCON cell, it may be possible for the theoretical minimum to be exceeded over a longer time frame.

Regarding the volume (Weight of chips per 20k parts [kg]) of chips recorded at this location, other than some natural oscillations, there is no significant change at this time. This is to be expected, as interventions regarding the small chips (which constitute the largest share of material carried over) have only been tested experimentally and not yet implemented in the production cell (This report will asses and justify the implementation of such interventions). The overall reduction of approximately 20% for this figure, could potentially be in part attributed to the lower volume of discs present at this site as well as any minimum positive contribution that the robotic motion has on the smaller chips. Overall, this variation should not be considered for the aim and purposes of this study.

The removal of smaller chip types is evaluated in section 7.3.2 and section 7.3.4. In other words, the robotic handling motion cannot, by itself, reduce the gross volume of chips carried over, but only the presence of disc burrs in the mix. A reduction in this value will only be visible after the implementation of the other solutions presented in this report.

Finally, the data collection and evaluation of Chip Presence at the EDC Facility (section 7.1) has now introduced an established metric that in the future, will allow to continuously monitor the progress in the constant pursuit of better manufacturing strategies regarding the chip carryover phenomenon.

7.2 Implications on Downstream Processes

Following the manufacturing process, the most relevant and comprehensive assessment of the implemented solutions and how effective they can be to manage the chip carryover problem, can be conducted during functional testing (before the parts are assembled). All parts that should fail this assessment are manually inspected; results from this operation are registered and can be used to link failures with the potential presence of chip. Figure 7.2 provides a comparative analysis of the failures in the downstream processes, over a similar time period, before and after changes in the LiCON cell were implemented in week 5 of 2023. The data in figure 7.2 is presented with the cumulative failures for all parts that were machined in the LiCON center separated from parts manufactured by Heller machines.

With constantly increasing production volumes, the manufacturing of calipers at this site is in a transition from the older Heller machines to the newer LiCON cell presented in this study, and an upcoming investment which will consist of another LiCON cell being installed. Consequently, a larger share of the calipers is being produced by the LiCON machines year over year, as the Heller machines have been gradually converted to the machining of other components. While throughout 2022 LiCON constituted approximately 46% of the total failures in performed tests, early 2023 shows a remarkably different behaviour.

Following the implementation of the new robotic motion (presented with greater detail in section 7.3.3 in week 5, the LiCON cell has virtually been responsible of no issues in downstream processes (According to data up until week 16). Of the two failures since the beginning of the year, one has occurred in January before any changes had been implemented, and the second one in February around the time the new robotic motion was being implemented. Despite gradual decrease in the produced volumes, the Heller machines (where no improvements have been implemented) are still causing a significant number of parts having problems during later manufacturing steps. In line with the discussion of chip carryover to the EDC station, the number of failures in testing are likewise a probabilistic matter. A smaller number of chips recorded at the EDC station will translate into a proportionally reduced chance of encountering chips in the tested parts. Given the non deterministic behaviour of this solution, fluctuations are to be expected. Nevertheless, the positive effect on the sudden absence of failures (by contribution of parts machined in the LiCON cell) during March and April is likely related to the implementation of the new robotic motion. Additionally, a decrease in failures on the Heller line during the months of March and April can be attributed to a change in the production organization taking place during this period. Production on the Heller machines has in fact been gradually converted to brake carriers exclusively as calipers will be machined by the now expanding LiCON cell.

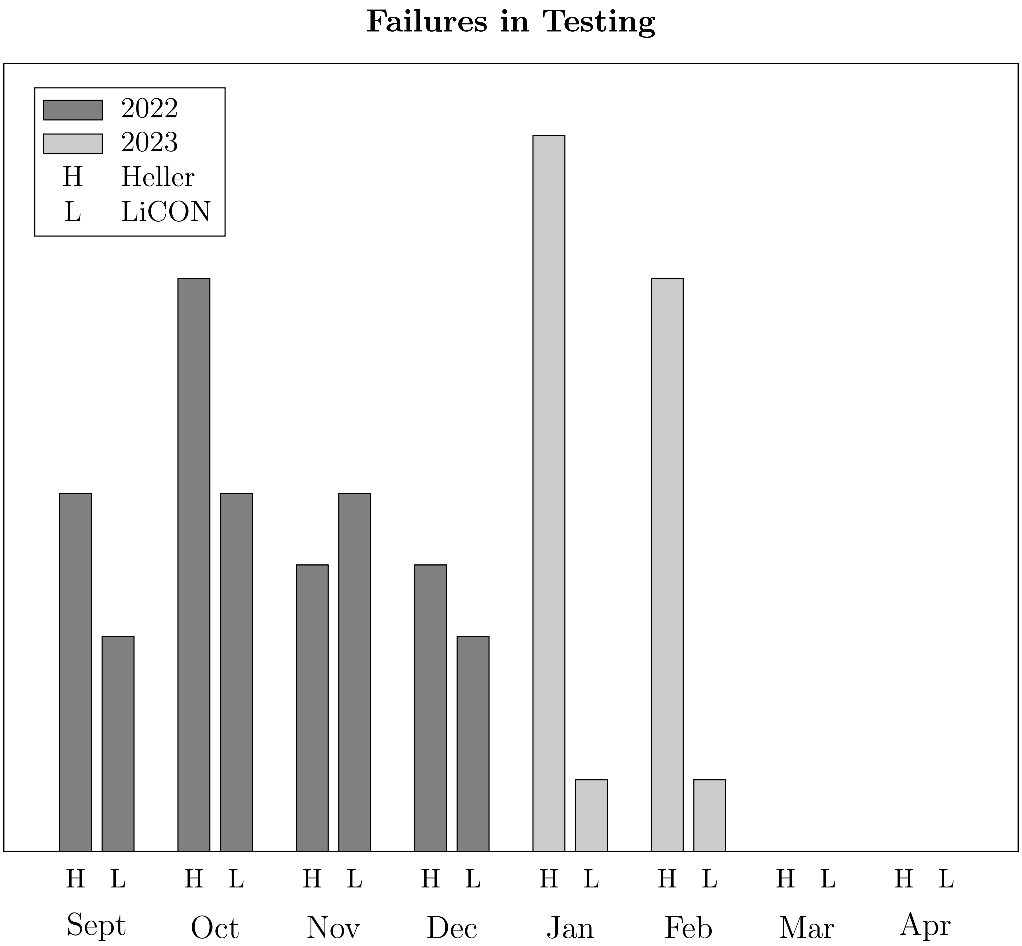


Figure 7.2: Comparative plot of failures in the downstream processes for the disc calipers (22" model), due to presence of chips or burrs in the inside cavity of the product (September´22 - April´23)*.

7.3 Evaluation of the Implemented Solutions

Among the proposal of possible implementations in section 6, a selection of these suggestions has been implemented at the facility. The following subsections present a critical

*The data collected was updated in week 16. Additionally, there is two failures in the month of March that have not been allocated to either of the production lines (LiCON/Heller).

assessment of these solutions and how they influence the performance of the manufacturing process.

It is important to be aware that the decisions made while implementing new solutions are bound to the company wishes as well as progressive development and continuous evaluation of the production scenario. Therefore, while the principles behind the implemented solutions presented in this section are the same as the ones discussed in section 6, in practice, there have been some adaptations and simplifications to better meet all of the functional requirements for this project.

7.3.1 Evaluation of Cast Design

Potential implementations to the cast design are evaluated primarily on the influence that this has on the presence of chips and disc burrs following machining operations. For this reason, the main focus was placed on reaching a deeper comprehension of how casted surfaces influence the formation of the aforementioned burrs and what changes to the surface topology would support a more effective way of removing these chips. To achieve this, drilling experiments were conducted in a test laboratory set up, where operations and observations could be carefully conducted. The specimen for these experiments were prepared utilizing material of the same alloy and that was casted in the same manner as the brake caliper in which the formation of disc burrs regularly occurs; therefore, the bulk material properties of the sample can be assumed identical to those of the workpiece. Nevertheless, in certain cases, the sample´s surface differed from the real workpiece as the ball blasting surface treatment that is performed on each of the calipers generally does not affect the inside geometries of the workpiece, but was present on some of the sample material. Although potentially significant, these different surface properties do not translate to the results of the tests hereby presented, as experimentally observed.

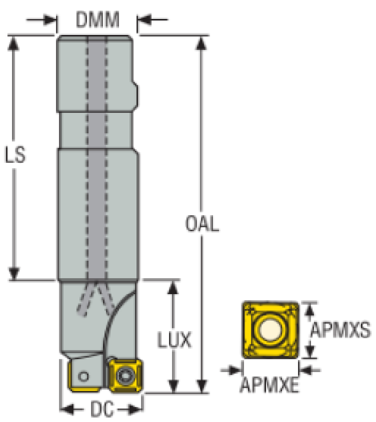


Figure 7.3: Drawing and image of the tool used for testing of different cast designs (Seco Tools 2023).

Due to machine-tool compatibility, the tool used for these operations was not tool T517 itself but a similar tool (R417.19-2530.3-09A) by Seco Tools (Seco Tools 2023). This tool presents a similar, yet marginally simplified, cutting edge geometry which is visible in figure 7.3. In a preliminary testing of this tool, conducted on the same surface as T517 would (Seen in the first row of table 7.1), it was noticed that this tool produces very prominent disc burrs that are to all extents comparable to the ones found in the LiCON cell (Visible in figure 5.11). In other words, if a solution was to be assessed to beneficial for this tool, it is reasonable to believe that operations performed with tool T517 would also be positively affected by it. Finally, different geometries and orientations were tested to understand the influence that the topology of exit surfaces has on the formation of the disc burrs. A summary of the experimental results can be consulted in table 7.1.

Naturally, the experimental practice has illustrated both some effective and less effective solutions in terms of the resulting chip formation. Particularly the surfaces illustrated in rows 2,4,5,7,8 of table 7.1 provided some very solid and preposterous disc like burrs which should ideally be completely avoided. On the other hand, the remaining experiments (visible in rows 1,3,6,9) had a positive outcome and provided useful insights for the design of an improved drill exit surface. First of all, the *sloped exit* (angled at approximately 30° from the horizontal plane) in row 3, caused the chip to completely fold on itself, effectively reducing its size by half. Similarly, the *central edge-line* in row 9, caused the chip to fold in half; this time however, the disc burr was thicker and apparently less prone to break in two smaller parts, as opposed to the previous case. The interesting aspect of this feature is indeed the presence of a locally confined slope of 30° on an otherwise flat (and perpendicular to the drilling direction) surface. The *sloped exit* and *central edge-line* are graphically illustrated in figure 7.4. As the results suggest, both surfaces provide effective solutions to the problem by imparting a folding/rolling action during the formation of disc burrs; however, this occurs in a significantly different manner for each of the surfaces. When encountering a slanted exit, the disc burr will begin to detach from the workpiece where the drill will first pierce through the surface; thereafter, as the disc burr forms it is progressively rolled onto itself until the drilling operation is completed, and the burr detaches.

In contrast, the *central edge-line* implies that the disc burr is formed in two separate stages, separated by a local sloped section, in the same way as in the flat exit (row 2). Because of this unique configuration, the result is that the *central edge-line* produces two half-discs, folded onto each other by effect of a local variation in the exit angle. Once again, this behaviour is graphically illustrated in figure 7.4. As opposed to the *central edge-line*, the continuous rolling over action, combined with the steady support offered by the *sloped exit* surface that has not yet been cut, allows the tool to cut into the material to a greater extent before the material fails by effect of the axial feed, and the burr breaks loose from the bulk material. In essence, the practical effect is that fully sloped exits result in a curled and relatively thin disc, whereas the localized slope results in a thicker disc folded in half and onto itself. The beneficial effect imparted by the presence of a *large indent* as the one illustrated in row 6 of table 7.1, is technically very similar to what described for the *sloped exit* and *central edge-line*, with the main difference that the relative position and entity (shape, size, depth) of the indent will cause the chip to roll over, fold, or even break, at different positions.

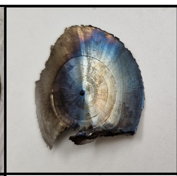
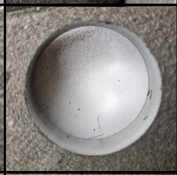
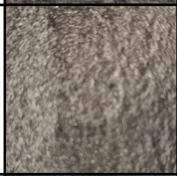
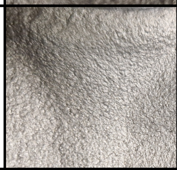
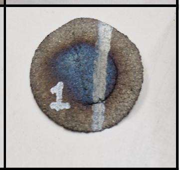
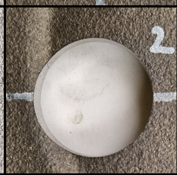
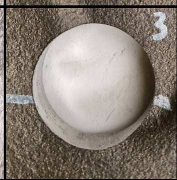
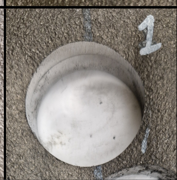
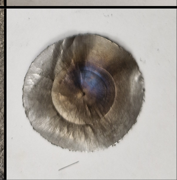
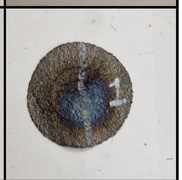
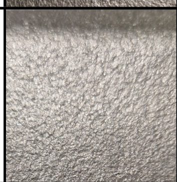
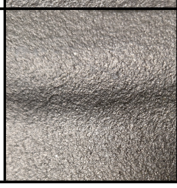
Row	Comment	Surface	Hole	Disc Back	Disc Front
1	Regular				
2	Flat exit				
3	Sloped exit				
4	Concave surface				
5	Small off-set edge-line				
6	Large indent				
7	Concave & sloped exit				
8	Off-set edge				
9	Central edge-line				

Table 7.1: Experimental results for exit surfaces.

Despite some of the tested exit surfaces not providing a final result in terms of avoiding the formation of disc burrs, there is still a lot that can be learned from these experiences. Most remarkably, the *concave surface* (row 4) produces a very thin disc with curled edges and with signs suggesting that a greater concavity would reduce the diameter of the disc, as the outer edge would thereby be machined away in the form of small chips.

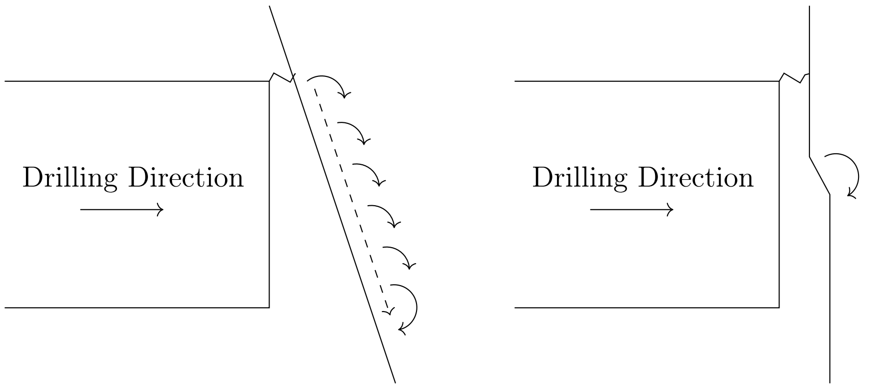


Figure 7.4: Burr formation approaching the exit during drilling operations; constantly sloped surface and centralized local slope (central edge-line).

An additional consideration is that the presence of a large pocket as the one visible in the top right corner of figure 3.2 is without any doubt less beneficial to how the coating is applied at the EDC facility. While methods to address this issue include oscillating the calipers in the coating bath to allow the coating fluids to fill air pockets, this can be quite trivial as opposed to a functional design for production iteration on the caliper, that would address the problem at its origin.

The results attained through the drilling experiments thereby support the idea of transitioning into an updated exit surface of feature ② potentially involving a central edge-line applied to an overall concave surface. Practical experience shows that resulting disc burrs would be less prominent and with a higher tendency to fold in half. By doing so, the reduced dimension of the burrs would favour their removal from the inside geometries of the workpiece and cause less problems in the downstream production processes. These findings are also supported by the theory presented in section 2 according to which, the presence of a slope and increased support on the perimeter of the feature should result in less prominent disc burrs by the exit of a drilled hole.

While these suggestions can already be employed for a new iteration of the cast design, this can be quite an involved process which might require a significant amount of time. Because of this, design for production and topology optimization of exit surfaces for insert mill drilling could be an interesting topic for future thesis research.

7.3.2 Evaluation of Reviewed CAF

As one of the most beneficial implementations was evaluated to be the removal of the flushing sequence to reduce the LiCON machines' cycle time, it became necessary to develop an alternative solution. Implementing a CAF to address chip accumulation on the machined calipers effectively means that the internal flushing can be replaced by an external solution which does not require additional machine time. Among possible solutions, the two that appeared most interesting were the construction of a dedicated fixture which would clean the calipers and the pallet carriers they are on while moving along the conveyor belt, or to reconfigure a CAF roughly based on the existing design. Unlike mentioned in section 6.2.1, combining a robotic handling motion with a CAF was eventually found to be unnecessarily complicated.

The handling movement described in section 7.3.3 was proven to be extraordinarily effective at removing the large disc burrs from inside geometry of the machined calipers (as reported in figure 7.1) with minimum required effort from an implementation point of view. On the other hand, as it will be further discussed, practical experiments brought to attention that a reviewed CAF design could become an effective way of removing all small chips that accumulate on the outside surfaces of the machined calipers. Additionally, the placement of these upgraded cleaning fixtures could be such to address the parts directly as they are taken out from the machine and, by doing so, minimize the potential for chips ending up on the floor or interfering with the moving part of the conveyor system.

Eventually, these observations ended up steering the project away from the development of a carrier cleaner, for which the placement of compressed air nozzles would be limited by the restricted space available and might not be as flexible to accommodate future changes in the product. Although the current caliper has proven to be compatible with nozzle placements on the side, it remains uncertain if future caliper generations will share the same compatibility. Because of its easy access and application, compressed air was chosen as the preferred medium to perform cleaning operations. While different mediums such as coolant and cutting fluids have also been considered, their application required a more involved system with no apparent benefits over the already satisfactory compressed air solution. This decision was in large part based on a "proof of concept" assessment which was performed as a preliminary evaluation for the possible development of a carrier cleaner or revised CAF.

The experiments were conducted by placing machined calipers on a conveyor carrier which would replicate how the parts are normally positioned in the LiCON cell, and individually evaluating what directions and positions would grant access to a stream of compressed air that would remove the chips from the workpiece's surface. To mimic conditions in the cell, the calipers were prepared by applying short chip and cutting fluid in multiple layers in the areas where chips are known to be accumulating. After waiting approximately one minute for the fluid to set and bind with the chips, the caliper was turned around and back to get rid of excessive cutting fluid and loose chips. This preparation sequence resulted in brake calipers that closely resembled the parts when exiting the LiCON machines.

The experimental results had a positive outcome and were effective at chip removal for the locations hosting a majority of the chips which were not addressed in the previous CAF solutions. The particularly problematic regions are presented in figure 5.16. This approach was also proven effective at removing chips and residue from feature ① and feature ②. Nozzle placement was focused on the sides of the set up, so to assess the feasibility of the carrier cleaner where access to the caliper would have been limited by the available spatial configuration of the solution. The carrier experimentation involved testing six theoretical nozzle placements, as presented in figure 7.5. One of these nozzle placements was primarily intended to clean the carrier itself. The setup was found to be effective in cleaning the carrier when the blowing was performed in a specific sequence, for example, blowing the left side first and then the right side. Finally, what emerged from this experience is how precise nozzle placement is in practice far more important than air pressure or volumetric flow.

Figure 7.5: Directions for compressed air to effectively clear chips from the brake calipers (Experimental results).

The development of the revised CAF was grounded on the necessity of having a more effective apparatus which could fulfill its tasks of removing chips from the machined calipers. A few adaptations and additions have been made to the original CAF design, originally employed in the LiCON cell. Figure 7.6 presents views from the CAD assembly of the new CAF that was designed. This fixture now features a larger enclosure to allow chips to be evacuated from the machined calipers, via carefully positioned nozzles (shown in figure 7.7), and avoid the risk of them being transported back onto the workpiece. The implementation of a removable tray at the bottom of the apparatus allows to remove the chips that may accumulate after several cleaning operations. Additionally, with an integrated filtering false-bottom, any cutting fluid which may have been carried over with the machined parts could be collected independently. Separating the solid chips from the cutting fluids implies that each of the two wastes can be disposed and recycled in the most appropriate way. Furthermore, this will reduce the risk for the operators who perform regular cleaning and maintenance on these fixtures, to get in contact with the harmful fluids. The sides of the main box enclosure present a sloped surface in the bottom section which ensures that all chips are gathered in the removable tray and wont interfere with its operation. This solution is constructed to handle a pair of calipers at the time, similarly to how the current CAF does, and in line with with the machining operations in the LiCON machining centers, likewise carried out in pairs of two per cycle.

After the initial testing that brought to the development of this new CAF design, the precise final position of the compressed air nozzles was determined utilizing sections of flexible hoses and a similar procedure to the one described earlier in this section. Figure

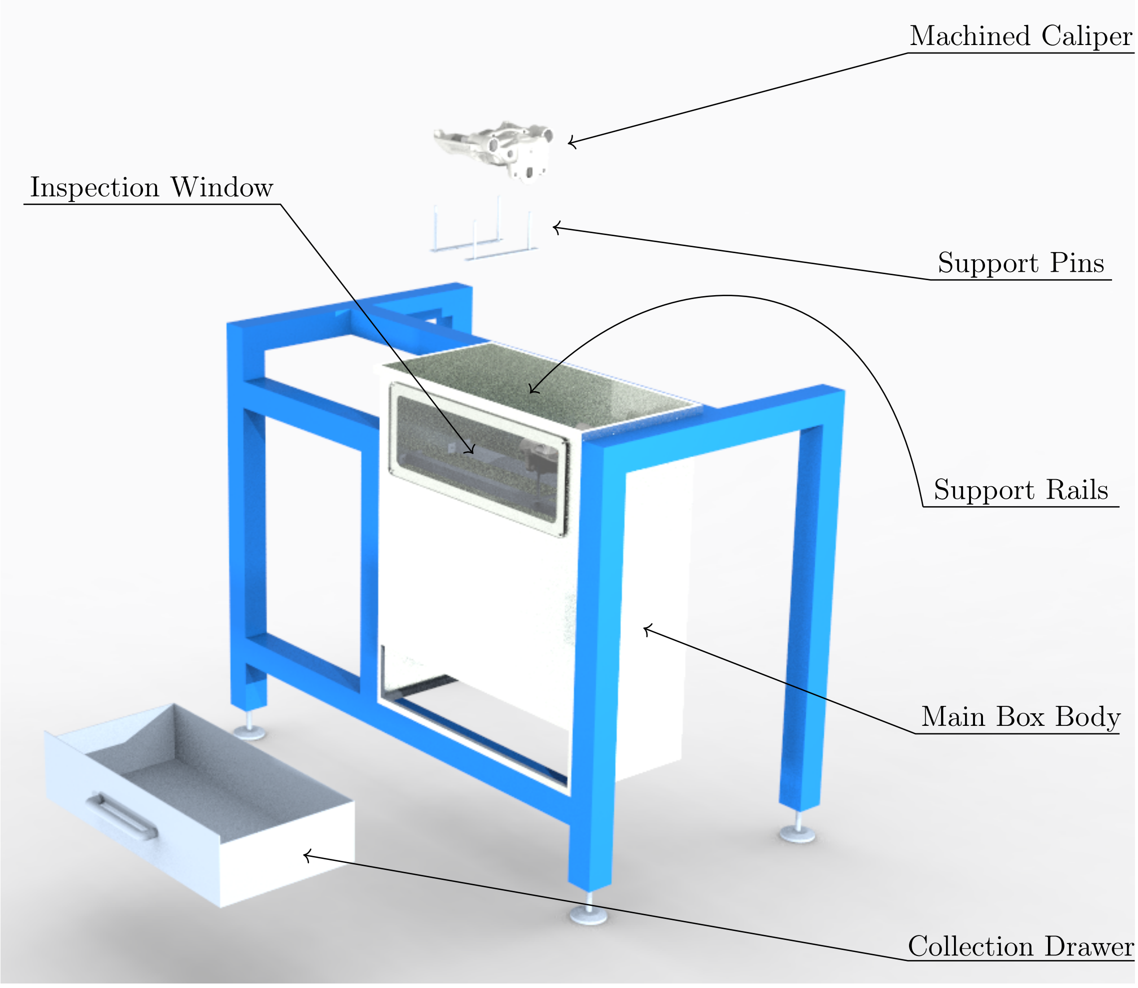


Figure 7.6: Rendering of the revised CAF assembly in a CAD environment.

7.7 shows a prototype version of the fixturing and nozzles that will then be permanently installed into the main box enclosure.

At this stage, experimental procedures and construction of the newly developed CAF have been focused and limited to the main functional components of this fixture, visible in figure 7.7. That is, the rails and the pins on which the brake calipers are rested, and the nozzles that direct compressed air to perform the cleaning operation. Note that at this time, the nozzles are fastened and assembled in a provisional way that has allowed to perform adjustments and tuning of the direction and position relative to the brake calipers for the compressed air streams. Once this prototype will be approved by the company, the recommendation would be to use metal piping for the air lines and nozzles, similar to the hydraulic brake conduits commonly used in the automotive industry.

Similarly, to aid the durability of this CAF the contact pins on which the brake calipers are rested should be made out of solid material, the same way these are constructed for the pallet carriers that carry the workpieces along the conveyor belt in the LiCON cell (A glimpse of these carriers can be vaguely seen in figure 7.5). The rail and nozzles hereby presented will be assembled in the larger box body visible in figure 7.6, which will in turn be installed in the already existing frames (The blue structure in figure 7.6) currently used to support the previous version of the compressed air fixtures. Additionally, the final

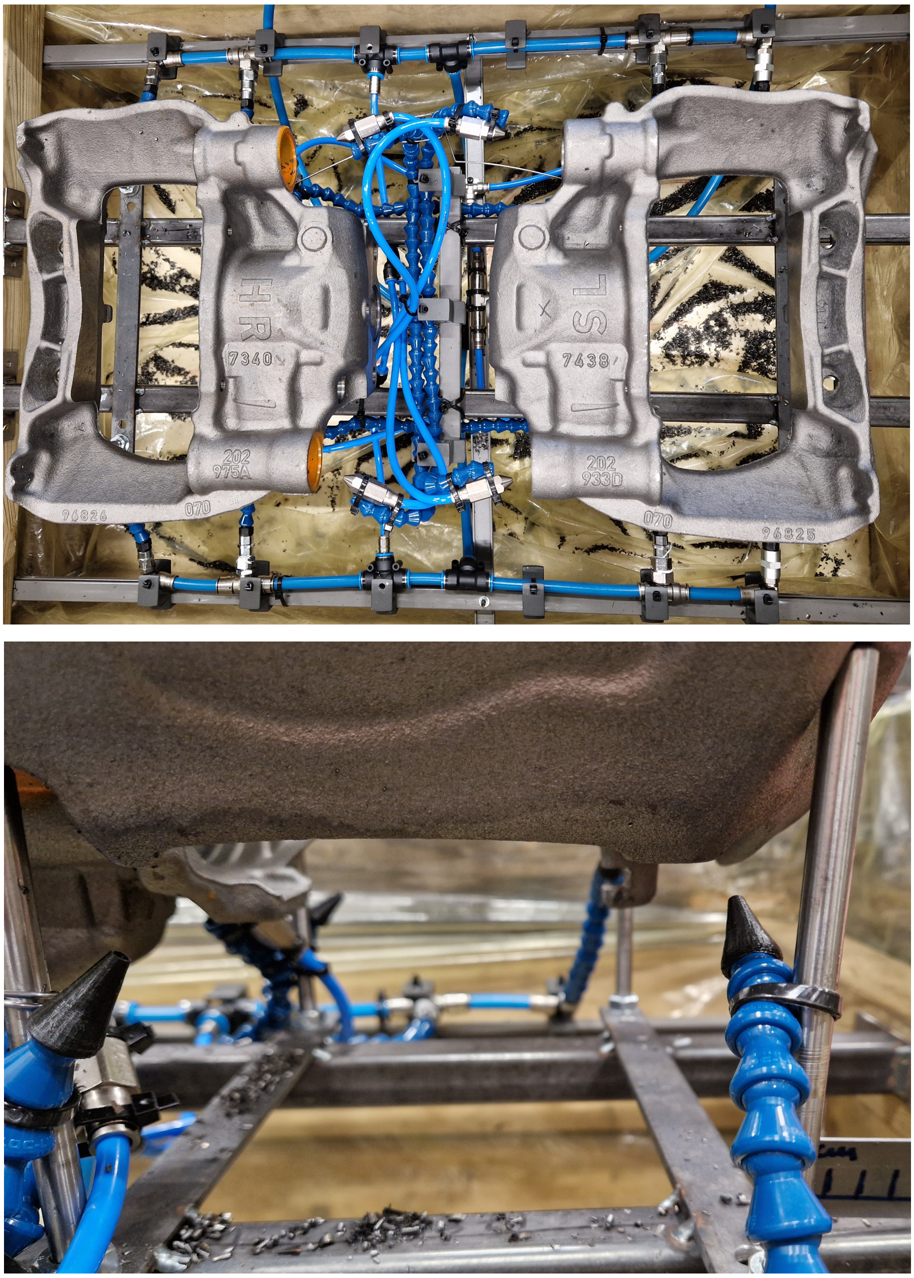


Figure 7.7: Experimental set-up for nozzle positioning in the revised CAF.

implementation of the five CAF needed in the LiCON cell will have to be interfaced with the automation for autonomous execution of the cleaning cycle, as well as with the robotic arm handling the workpieces. In practice, this will involve the installation of suitable solenoid valves for the supply of compressed air and defining the key-points required to update the motion of the robotic arm.

7.3.3 Evaluation of Handling Solutions.

Adaptations to the handling motion performed by the robotic arm at the centre of the LiCON cell have been made to optimize the removal of persistent chips and discs which may remain trapped in the inside geometries of the brake calipers. Previously, this motion was conducted in three orientations followed with a small motion with an abrupt stop to get the discs loosened. However, this sequence was not specifically engineered for discs but to address chips in general, and with only marginal knowledge about the chip carryover phenomenon. A revision of the operation illuminated a few key opportunities to improve its performance.

First and foremost, the main escape route to remove chips or burrs from the inside geometry was changed. Originally, the caliper was held by the robot in such an orientation chips had to exit by a small opening, with the new sequence the part is reoriented to allow a larger opening on the escape route from the inside cavities of the workpiece. This larger opening is where the mechanism actuating the brake pads will be installed. Secondary, although an abrupt motion might be effective at loosening chips and discs from the calipers surface, the old sequence did not encompass a following motion to effectively remove the material that was made free. Therefore, in the new sequence this concept is utilized with the addition and planning of a motion that aids in transporting any discs that might be present, out of the internal cavities of the brake caliper. In addition to that, the internal backside (opposite side to the large opening) is relatively flat and has no apparent features that could cause discs to get stuck. Discs could hence be moved along the surface of the internal geometry; from the pocket, along the back and side of the inside cavity of the caliper, and thereafter exit through the large opening.

Having developed a deeper understanding of how the cumbersome disc burr and larger chips behave once trapped in the inner geometries of the workpiece, a new improved handling sequence could be implemented with the goal of removing all burrs which may cause problems later in the manufacturing process. Figure 7.8 presents a step by step illustration of the new operation (Six steps marked ❶ to ❻) . With the first motion (❶), the caliper is rotated to prepare for the slight motion with an abrupt stop (in operation ❷) in order to loosen the disc. The slight tilt is intended to allow loosening of discs stuck above the pillar as well as in the deepest corner of the pocket. After operation ❶ and ❷ the caliper is rotated (in operation ❸) approximately 225° at an appropriate rate for the disc to roll or slide on the backside of the caliper and out via the large opening. Operations ❶ through ❸ addresses the disc removal of one of the inherent caliper orientations.

In order to account for the left and right orientation in the cast design (which inevitably require different movements to evacuate discs that may have been trapped in the inside geometries) the new handling sequence encompasses the additional steps, ❹ through ❻. These steps have the same function of steps ❶ to ❸ but have been mirrored to function with a opposite design orientation. Furthermore, the robotic arm performing this motion has additional overcapacity, despite the implementation of the new sequence. Therefore, should there be the necessity, it would still be possible to make use of this additional time to perform other tasks or further developments of the chip removal operation.

This implementation was dedicated to increase the effectiveness of removing discs stuck in the internal geometry of the caliper. General chip volumes were not a target for this implementation nor was it expected to affect it, which is also reflected in the followup data collection at the EDC station presented in figure 7.1. As previously mentioned, the LiCON cell predominantly handles 22" calipers, hence why this implementation mainly focuses on

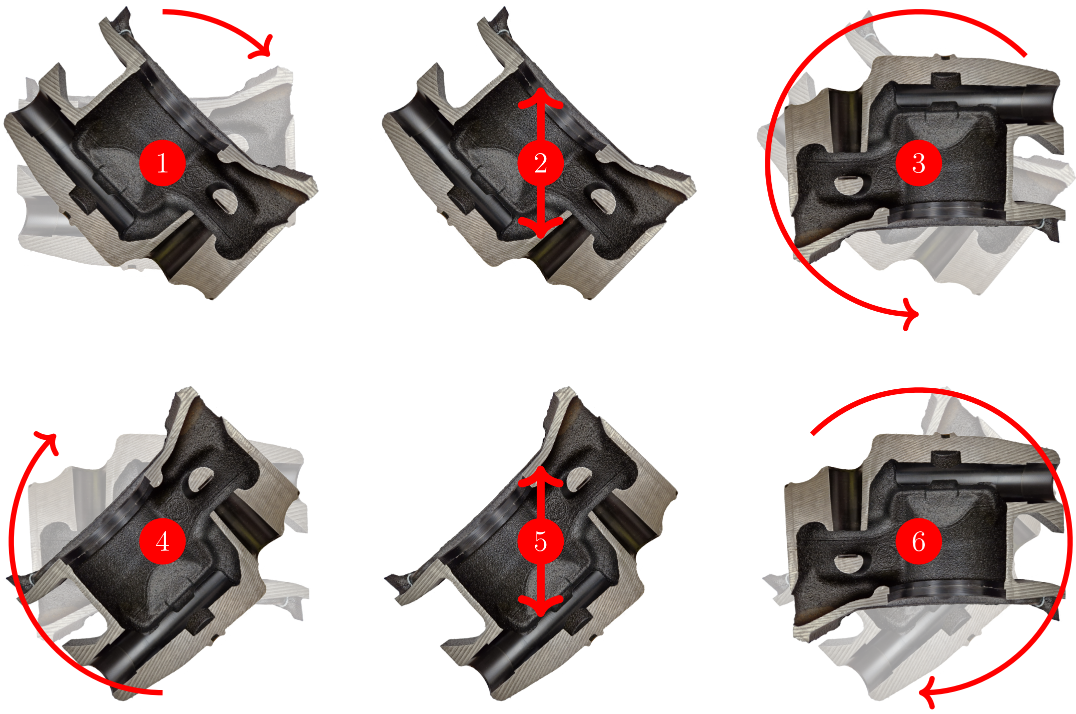


Figure 7.8: Sequence of handling positions for the updated robotic motion.

this aspect. During the time presence of chips at the EDC station was investigated, the results converged towards a value suggesting that all chips from the 22" calipers machined in the LiCON cell are addressed before these make it to the EDC facility. In other words, no more discs from the LiCON cell are carried over to the following process (At least from a theoretical and numerical stand point; possible exceptions are to be considered as such). Although not initially expected, the overall weight of chips per produced part also experienced a slight reduction of 20% which may be attributed to slightly longer handling operation and more intense movement of the machined parts by the robotic arm.

Monitoring of issues in the downstream processes aligns with the results of data collection at the EDC station, as visible in figure 7.2. The new handling motion has a positive effect on the number of parts that fail the functional test due to the presence of carried over disc burrs in the mechanism.Nonetheless, claiming that this implementation by itself would eliminate any issues in the downstream processes is not correct, as in the holistic approach of this study, the solution to the chip carryover phenomenon and its implications can only be achieved if an integrated strategy (consisting of multiple implementations each addressing different stages of the manufacturing process) is adopted. To fully ensure a complete elimination of the presence of disc burrs, the one and only reasonable solution would be to address this issue where it originates, during the machining operations.

7.3.4 Evaluation of Machine Operations

This section presents an evaluation of the potential implementations that affect how operations are conducted inside each of the LiCON milling centers. These include cutting data, cooling and flushing, and the machining sequence, as described in section 6.4.

To address the formation of the disc burrs, formed during the machining operation of feature ② (as illustrated in figure 5.1), a variation in the value for the axial feed of the tool has been considered, in line with what was suggested by the currently available academic research (See section 2.1.4 for a detailed overview). Following the suggestion presented in section 6.4.1, access to the LiCON machine program file was made possible by the company. An extensive investigation of the NC code has revealed the presence of discrepancies in the codes for different machines and, even more interestingly, in the values of cutting data for different operations such as the sections illustrated below.

```
% Generic NC code for left and right calipers
N5860 G1 Z=59.5+0.25 F=200 D2

% LiCON 2 - Right hand caliper
N6400 G1 Z=59.5+0.25+1.2 F=200 D2
N6410 G1 Z=59.5+0.25 F=50 D2
```

In 2019 an experiment was conducted to evaluate the effect of reduced feed in the final segment of the drilling operation of ② by tool T517. This section of modified code has unintentionally not been removed from one of the machine programs, and has since then been running on LiCON 2. Furthermore, this change has only been providing a positive influence to the cutting data for the machining sequence of the SAF right hand caliper, which is known to otherwise be the most affected by failures due to the presence of chips in its inside geometry (as illustrated in section 4.2.3). As is evident in the NC code presented above, there is a a distinct difference between the LiCON 2 (right hand orientation) program and the program running on all other machines. The final 1.2 mm of the drilling operation of feature ②, conducted by tool T517, are conducted at a reduced feed value. An illustration of the machining regions of tool T517 and T4172 is presented in figure 7.9 along with the region affected by a feed reduction (yellow hatching).

Figure 7.9: Tool utilization in machining and feed reduction region in machining of feature ②.

In this different code, the feed is reduced from 200 to 50 mm/min, while the spindle speed and cutting velocity v_c remain unchanged. At this lower feed rate the axial forces responsible for the detachment of the disc burrs are also reduced. Consequently, this portion of material is machined to a greater extent resulting in the formation of a thinner disc, presented in figure 7.10. The top row in this figure presents discs collected from LiCON 3, where right hand calipers are machined at 200 mm/min feed. While the section below, presents discs generated by right hand calipers machined in LiCON 2 at a feed of 50 mm/min.

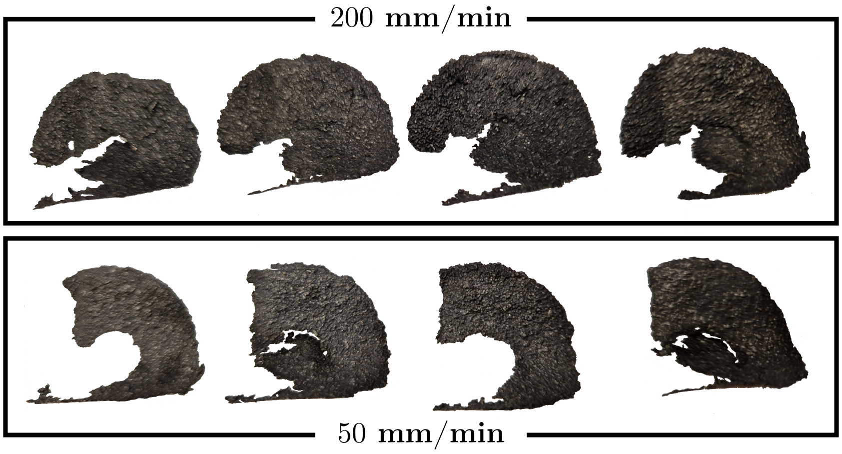


Figure 7.10: Variation of chip formation in relation to the nominal feed f_{nom}.

It is evident that at a reduced feed rate there is higher chip fragmentation, that is, the formed disc burrs are smaller and thinner. All four discs in figure 7.10 (machined with a reduced feed rate) had the region where the indent was originally located (See figure 5.10 for reference), separated from the disc (as analyzed in detail in 5.1) as well as signs of greater fragmentation in the central region of the burr. Nonetheless, reducing the feed rate any further may not result in desirable results since the theoretical chip thickness h_1 may be approaching its minimum theoretical value h_{1min}. When this occurs, strain hardening of the machined surface and higher tool wear are to be expected, as well as worse chip formation characteristics.

In general, defining an optimum level of h_1 for favourable disc formation (or absence thereof) is a rather involved process which requires careful considerations both from a choice of tooling and chip formation theory perspective. Nevertheless, the ideal behaviour will likely be achieved in the region $h_{1min} < h_1 < \varepsilon_{III}$ as explained in greater detail in section 2.1.3, Chip Formation.

Reducing the feed also implies a trade-off between tool life and effectiveness in conducting the drilling operation, as the tool will be subjected to additional wear due to increased machining of strain hardened material. Despite having a minimal effect on shorter trajectories, lower values of feed will also contribute to a longer DOO because of the reduced material removal rate. The balance between the two factors is found where the cost of tooling and increased machine time meet the cost of removal of chips and burrs that persist in the machined parts.

To summarize, despite intuition may suggest the opposite, an excessive reduction in the feed rate result in increased disc burr thickness. This is true in the limits of machinability imposed by the minimum theoretical chip thickness h_{1min}. By transitioning to inserts with a smaller edge radius r_β, this limiting value can be adjusted to allow even lower feed rates, while not encountering the strain hardening issues previously described.

Figure 7.11 reports the failures during testing in later stages of the manufacturing process, sorted by which LiCON center has machined the brake caliper. Thanks to data from past experimentation, it was possible to evaluate the effect of reduced feed rate over an extended time span and correlate its influence on the failures during testing for two full years (2021-2022). In line with this phenomenon and lack of opposing factors, it is believed that the reduced feed rate (in the right hand orientation exclusively) is the main contributor as to why LiCON 2 sees similar success in the machining of the right orientation of the caliper as that of LiCON 1 (achieved because of a favourable sequence and strategic flushing).

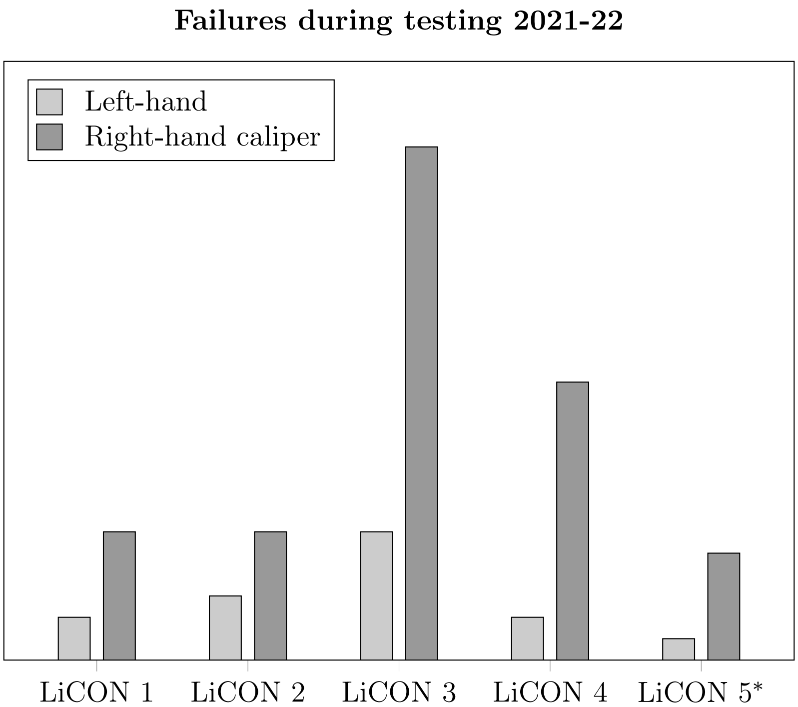


Figure 7.11: Failures connected to presence of chips in the calipers at later manufacturing stages, sorted by machine center in the LiCON cell and Left/Right caliper orientation (2021-2022).

While one may argue that data presented in figure 7.11 may be linked individual machine behaviour, since LiCON 1 and 2 have similar results in both left and right caliper failures, there is sufficient evidence to rule out this possibility for bias. All machine centers centers apart from LiCON 3, present a similar count of failures in the left hand calipers, accounting for the partial production of 22" calipers in LiCON 5 (see footnote in figure 7.11). On the other hand, the number of failures for the right caliper orientation fluctuates to a great degree, depending on the machine center. LiCON 4 is a great example of that

*Production on LiCON 5 is shared by two different product lines therefore, while failures for the 22" calipers object of this study, might seem low, this is because they are produced at only ∼ 50% rate on this machine.

as it has the same amount of left caliper failures as LiCON 1, but more than twice the amount of right caliper failures. Furthermore, LiCON 2 is running the same program as all other machining centers (apart from LiCON 1) with the exception of the reduced feed rate during drilling of feature ②. Its low count of failure is the right hand caliper orientation, suggests once again that this behaviour is not a result of the condition of each of the machining centers, but it is rather linked to the machine´s NC program and chosen cutting data.

Increasing the feed during the drilling operation of feature ④ as shown in figure 5.1, has been tested prior to this study. According to the tooling expert at the company, higher values for the axial feed during this operations are not sustainable for the two fluted twist drill bit that is currently employed for this operation. Figure 7.12 provides an image of the tool in question, where it is immediately visible that the cutting edge has catastrophically failed, in this case by effect of vibrations caused by higher feed values.

As this tool is already being investigated at the company, with the support of the tool suppliers, following this lead on a parallel path was deemed not to be of interest, and outside the scope of this project. Nevertheless, it can be mentioned that 3-fluted twist drill have been considered, as well as that current solutions are aiming towards an integrated tool capable of performing drilling and reaming operations simultaneously (as previously described, with better detail, in section 6.4.1).

Figure 7.12: Double fluted twist drill dedicated for machining of feature ④; detail of chipped cutting edge which caused tool failure.

From a broader perspective, machine operations do not only entail the tool specific cutting data but also the sequence in which operations are performed. Besides the necessity of performing certain operations in a specific order (i.e. a hole cannot be reamed if it has not been drilled yet), the sequence in which machining operations are carried out can be designed on a time efficiency regime or from an operational effectiveness point of view, depending if it is deemed more important to optimize the cycle time, perform operations in a certain way, or both. Although this topic could easily become a project of its own, throughout this study it has been suggested and proven that the machining sequence of operations has a direct effect on the chip carryover phenomenon.

Additionally to showing the benefits of the reduced feed for tool T517, figure 7.11 highlights that milling center LiCON 1 has the lowest contribution to failures in the testing of brake calipers before they can proceed to assembly. Upon a further investigation of the issue, it was brought to light that LiCON 1 operates on a different machine sequence which does not end with the machining of the problematic feature ②. On the contrary, the machining operation of feature ② is anticipated in the sequence, allowing the following movements of the machine and flushing action of the tools, to aid the evacuation of any disc burrs that may have been trapped in the inner cavities of the workpiece. While this finding does not meet the sequence proposed in section 6.4.3 (which has not been tested in its entirety for reasons that will be explained later in this paragraph), it unequivocally proves that there is a lot that can be gained by performing changes to the current machine program files. This means that by only adapting all LiCON machines to the sequence performed in LiCON 1, the presence of persisting disc burrs could potentially be reduced by over 50%.

Despite the obvious and immediate benefits which this simple implementation would provide, there is a few aspects that should be kept in mind. First and most important, is the order in which tools are stored in the machine's magazine; while changing the machine code is a relatively simple task, re-arranging the magazine to meet the new sequence is quite an involved and time consuming operation. Because of this reason, the technicians at the company have been hesitant to implement such changes. This raises the concern that future implementations may be restricted by the lack of testing conducted during the period of this study. Secondly, if other implementations such as handling solutions (section 6.3 and 7.3.3) can completely address the presence of disc burrs in the inside geometries of the workpiece, this implementation becomes virtually unnecessary. If this happens to be the case once other solutions have been implemented, then the focus should be to further develop the machining sequence to reduce cycle time and address the presence of smaller chips on the machined brake caliper. The sequence presented in table 6.1 proposes a solution that accounts for both aspects of the chip carryover phenomenon (presence of trapped disc burrs, and small chips on the outside surfaces), to reduce cycle time and potential issues in the following manufacturing steps. By doing so, it provides an established starting point for further cycle time optimization projects where, naturally, the internal flushing operation should not be encompassed.

7.4 Regarding Manufacturing Sustainability

This section primarily assesses the influence that changes in the current production context would have on the Triple Bottom Line. This is, primarily economic and environmental aspects, and to a minor extent social implications. Aspects concerning the monetary dimension of economic sustainability are presented in 7.5.

Regarding sustainability, the main benefits introduced by the implementation of the solutions suggested in this report, are connected to a better use of the available resources. Most notably, the transition from internal to external management of small chips introduces a significant reduction in the cycle time. This change allows for increased productivity and potentially lower energy consumption per produced part, thereby increasing the efficiency of the machining processes. From an economical and environmental perspective, this constitutes a leap towards the sustainable investment goals of improving energy efficiency and strive towards climate change mitigation. Furthermore, the increased productivity of the cell implies that there is capacity for manufacturing larger volumes of brake calipers and therefore, increase the profitability of operations at this manufacturing site. The organization is hence in a better position to be economically sustainable and make strides to improve the other dimensions of sustainability, through investments in research and development of energy efficient braking systems as well as manufacturing thereof.

Among the vast assortment of implementable solutions presented in this study, the common denominator is to prevent and reduce quality rejections, to ensure the highest standards in the finished products as well as reducing manufacturing costs. The revised robotic motion is an installment dedicated to removal of discs remaining in the internal housing of the caliper which require additional handling from the operators and can result in the part being scrapped. The suggestions on exit surfaces and cast design, is likewise a mean to reduce this effect and avoid negative effects on efficiency and performance, in the environmental and economical dimension. Improved CAF aid the removal of higher volumes of smaller chips which are otherwise present in large amounts. Ensuring a correct chip removal is instrumental to proper recycling methods, besides the benefit of not encountering these across the manufacturing facility. Chips currently remaining on the caliper after machining are partially being scattered and mixed with other materials and thereby cumbersome and inefficient to recycle. The CAF addresses chips earlier in the manufacturing process and separates them from any cutting fluid or oil which may be also be present on the machined parts.

The social aspect of sustainability could be further improved by a reduction of the potentially harmful presence of burrs and chips on the workpieces, as well as the above mentioned fluids. An increase in productivity should in theory not affect the requirements or strain on the operators, and increased profitability could allow for additional remuneration or training programs for the employees.

7.5 Economic Impact

This section provides an in-depth economic analysis for the proposed changes to the manufacturing strategy, tailored to the company hosting this research project. As such, this discussion is presented separately from section 7.4, Regarding Manufacturing Sustainability.

An additional layer of analysis hereby presented is defined by the economic impact that future possible implementations would have on the already existing flow of operations. In practice, this means that a differential cost analysis must be performed in order to assess and assist all decisions regarding the implementation of the developments previously suggested. This section presents a cost evaluation of three different scenarios; the first one being, how much is the cost of the machine time currently dedicated to the flushing sequence costing for the company. Secondly, following the current growth trend, how large would the profit be if the flushing time would be allocated to expand machine productivity. Finally, the third scenario illustrates a situation in which the flushing sequence is shortened rather than removed. This particular case is especially interesting as it highlights the presence of a ponderous fixed cost connected to the tool change sequence; therefore, suggesting an intermediate solution where the flushing operation is performed by one of the internally cooled tools rather than a dedicated arrangement.

The cost analysis hereby presented was based on the part cost model illustrated in section 2.4. Numerical data and cost related parameters were based from the latest update at the company, where indexes are measured in an ongoing manner. The investment cost of machinery was determined with an evenly distributed annuity influence across the investment time-span. This way, the depreciation of the investment can be translated into an hourly cost which is utilized as part of the hourly equipment cost variables (k_{CP} and k_{CS}). The annuity factor a_f was calculated in line with equation 4 and used as a multiplier to the initial investment, K_0.

$$a_f = \frac{p(1+p)^n}{(1+p)^n - 1} \tag{4}$$

An important consideration that must be elucidated before moving forward with the definition of the hourly equipment cost variables (k_{CP} and k_{CS}), is their dependency on the annual production time. That is, a given yearly cost is distributed on the planned hours the equipment is bound to be operational. Therefore on equal terms, for shorter planned yearly production time, the machine hourly cost will be higher and incise more on the part cost. Throughout this section, the hourly cost is assumed to be constant as the planned yearly production time is predefined and the equipment is assumed to be fully utilized during this period ($U_{RP} = 1$).

The complete part cost formula is presented in equation 5.

$$\begin{aligned} k = {} & \frac{k_A}{N_0}\left[\frac{1}{n_{pA}}\right] + \frac{k_B}{N_0}\left[\frac{N_0}{1-q_Q}\right] + \frac{k_{CP}}{60N_0}\left[\frac{t_0\,N_0}{(1-q_p)(1-q_Q)}\right] \\ & + \frac{k_{CS}}{60N_0}\left[\frac{t_0\,N_0\,q_S}{(1-q_Q)(1-q_p)(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_p\right] \\ & + \frac{k_D}{60N_0}\left[\frac{t_0\,N_0}{(1-q_Q)(1-q_p)(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_p\right] \\ & + \frac{1}{N_0}\Big[K_{AUH} + K_{CUH} + K_{GUH}\Big] \end{aligned} \tag{5}$$

Once the model has been fully defined, the part cost can be calculated for different production conditions by simply adjusting the relevant parameters. In the first, turning the cleaning of the caliper into external processing implies that the original cycle time t_0 can be reduced to a new cycle time t_0^* which does not encompass the presence of a flushing sequence. A differential part cost Δk can be obtained by subtracting the part cost for the current cycle time $k(t_0)$ with the one for the reduced cycle time $k(t_0^*)$ as illustrated in equation 6. This value effectively represents influence of the flushing sequence on the part cost.

$$\Delta k = \frac{\partial k(t_0)}{\partial t_0} \cdot \Delta t_0 = k(t_0^*, \ldots) - k(t_0, \ldots) \tag{6}$$

The yearly cost of the flushing sequence on the whole LiCON cell can be obtained by multiplying the change in part cost Δk by the total yearly production volume per LiCON machine Q and number of machines in a cell n such as in equation 7. The total cost connected to the flushing sequence in the LiCON cell (or the potential savings per cell, should the flushing sequence be removed) ΔK would be approximately 2.3 MSEK per year. This does not keep in account the potential for an increase in productivity which would in turn, also result in an increase in revenue.

$$\Delta K = nQ\Delta k = 2.25 \ \ MSEK/year \tag{7}$$

Reducing the cycle time per part implies the opening of free production capacity that can be used to increase the overall productivity of the cell. In this second scenario, the aim is to assess the potential profit that the company would see if following the elimination of the flushing sequence, the available time would be utilized to increase the production capacity. Since there is no set-up time T_{su} affecting production in the LiCON machines the calculation is simplified as illustrated in equation 8, where the change in production capacity ΔQ is calculated as $\frac{t_0}{t_0^*} - 1$ multiplied by the current yearly production volume per machine Q and number of machines per cell n. ΔQ expresses the theoretical increase in production capacity. Furthermore, it is known that machining operations will remain to be the bottleneck of the manufacturing processes at the facility, even after after the reduction in cycle time. Henceforth, the profit can be calculated as illustrated by equation 8. The potential yearly savings per cell (ΔK) as calculated in equation 7 are added to the increased yearly production margin margin. The margin on each produced part, M, is calculated by subtracting the production cost (in this case $k(t_{0^*})$) from the commercial value of the machined caliper.

$$Potential \ surplus = Qn\left(\frac{t_0}{t_0^*} - 1\right)M + \Delta K = 2.6 \ \ MSEK/year \tag{8}$$

Since there is no recurring set ups required for the machining operation of brake calipers within the LiCON cell, the relationship that can be established between the cycle time and the change in part cost is linear. Similarly, the total economic impact obtained when accounting for the increase in productivity, is directly proportional to a reduction in cycle time as presented in figure 7.13. A third scenario where partial flushing is implemented for the removal of particularly cumbersome chips can be assessed based on the same premises; this is illustrated in figure 7.13 as a dashed line. The economic impact of altering the cycle time has a fixed cost connected to the tool change and a variable dimension connected to the constant cost per second of machine time. Therefore, any time reduction for this operation is bound to a minimum yearly expense of 784 kSEK/cell, accounting for lost potential profits and assuming a one second long flushing operation. Any further extension of the flushing time would proportionally increase this value.

Furthermore, the evaluation of the cost for reduced flushing time is based on the time required for a tool change which amounts to approximately 1.3% of the cycle time, depending on the magazine layout of the machine in question. In conclusion, transitioning to a reduced flushing time is not advisable as the fixed cost connected to the tool change time is several times higher than the variable cost for the execution of the flushing operation.

To summarize this central aspect of discussion, figure 7.13 shows the relationship between cycle time, and the potential for the company to save in costs and generate more profit. While the major contributor is a reduction of part cost by effect of a shorter time in the machine, this also implies that free capacity will be made available. If this additional time is taken advantage of (to produce more parts and meet the rapidly increasing market demand) the company will be able to sell more products and generate a greater profit illustrated by the grey region in figure 7.13. Furthermore, by effect of the other implementations suggested throughout this report, the quality rejection ratio (scrap rate) will decrease. Finally, aspects such as a reduction in the scrapped material or a reduction in the required maintenance to to presence of chips, have not been accounted for in this calculations as they cannot be included in this cost model when applied exclusively to the LiCON cell. A more comprehensive simulation could be executed on the whole manufacturing process, potentially highlighting even greater benefits.

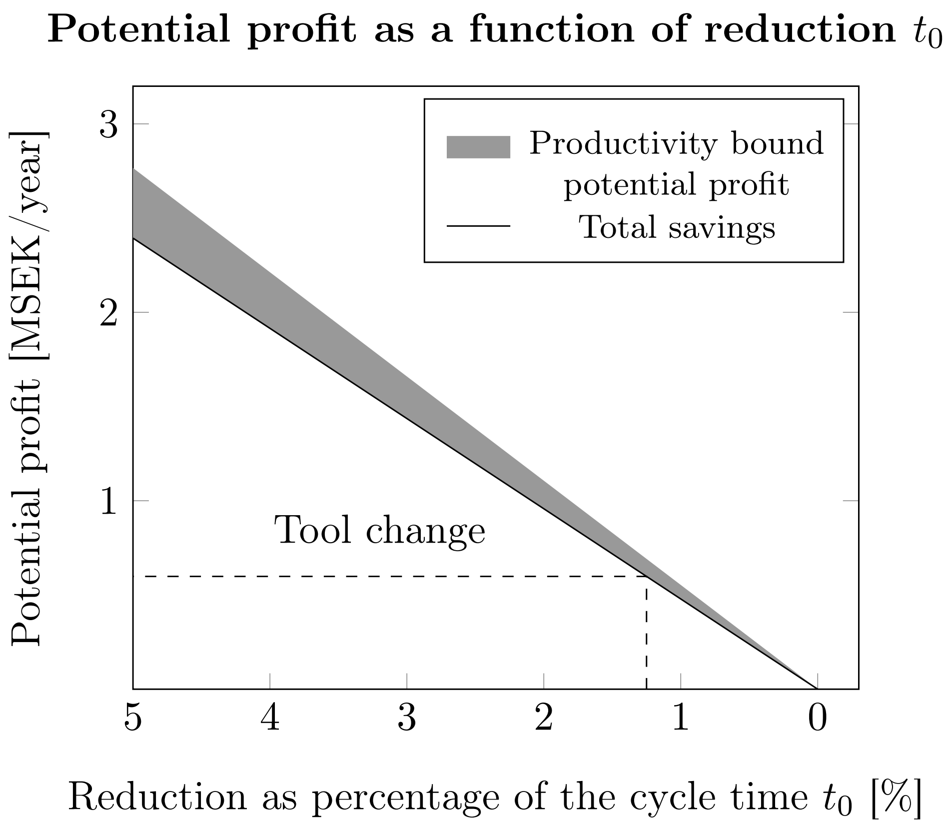


Figure 7.13: Potential profit per year and cell as a consequence of a reduced cycle time t_0.

Altogether, the cost analysis that was conducted in this project shows that the implementation of effective chip management strategies would be rewarded with significant yearly cost savings and the change to increase capacity for an overall larger profitability of the manufacturing operations. Conversely, some of the adaptations that are currently employed have been found to not only be ineffective but also economically not sustainable. In particular, the flushing sequence performed in the LiCON machines, not only costs millions of SEK per year in machine time and labour, but it also prevents the company to expand to their productivity potential and make full use of their resources. Finally, while not being part of the cost model, by addressing the chip carryover phenomenon there is potential for a large cost reduction benefit in reduced need for maintenance of the systems which would otherwise be continuously damaged by the vast presence of chips across the LiCON cell´s floor.

The presented manufacturing cost assessment was compiled and calculated with the aid of MATLAB. The script developed for the project can be found in the appendix and contains the framework which can be used to simulate the manufacturing cost in different scenarios.

7.6 Final Considerations and Discussion

The experimental data presented in the previous paragraphs brings to light some interesting results. It has been proven that the NC program in the milling centers and the sequence of operations can be strategically chosen such that existing supply of cutting fluid through the tool can act as a flushing operation to remove chips. This is also apparent in the failure statistics presented in figure 7.11 which revolves around the problematic disc burr created during tool exit of feature ②.

Approaches to resolving failures caused by these discs were also experimentally assessed with an assortment of different exit geometries to investigate if a favourable formation process could be achieved; these results are presented in table 7.1. Most notably, the central edge-line resulted in a beneficial folding action of the disc when compared to a fully sloped exit surface. The main difference is that the central edge-line tends to fold the disc on itself rather than curl it as apparent in the fully sloped exit. Additionally, the central edge-line would also reduce the intermittent cutting region, known to cause higher tool wear; this way, tool life may be extended. In general, the formation of burrs in the form of discs is not dictated by the exit geometry exclusively but is also influenced by the feed rate.

Lowering the feed rate to an appropriate level results in thinner disc burrs; combining this effect with the geometry of exit surfaces may lead to even more desirable outcomes. Furthermore, links have been established between time and management of flushing and set-up time with the association to SMED. In line with SMED, the economic potential of transforming internal chip removal (flushing) into external solutions (i.e CAF and robotic motion) has been highlighted. This change has proven to be of high value in terms of pure savings and increased manufacturing capacity. As the profit margin per produced brake caliper is expected to increase, the potential revenue from increased productivity will become even more impactful. Among the hypotheses presented in section 6 some have been deemed to be plausible and other verified, in line with the results presented throughout this section.

Hypothesis Evaluation:

To conclude the evaluation and discussion of the implemented/implementable solutions, the following considerations apply to the hypotheses that were developed in section 6 and section 7. The aim of this argumentation is to provide some general guidelines regarding what is the cause-effect correlation of changes in the production operations and what aspects should be kept under consideration to holistically intervene on the manufacturing strategies at any given site.

- ***H1*** - Effect of Cast Design on manufacturing processes.
  - ***H1.a****: Cast Design has a direct effect on the effectiveness of machining in the LiCON cell.* - **VERIFIED**

    The experimental results in section 7.3.1 show a direct correlation between the topology of the casted surface and the resulting drill exit burrs that occur in different disc forms, some of which are more prone to remaining trapped in the workpiece.
  - ***H1.b****: Cast Design has a direct effect on the assembly procedures.*

    As previously mentioned, this hypothesis can, for the scope of this project, only be discussed from a qualitative perspective. No metrics were established. The hypothesis was not evaluated.
  - ***H1.c****: Cast Design has a direct influence on operations at the EDC facility.* - **PLAUSIBLE**

    This hypothesis has not been verified in practice as cast design changes have not been implemented in the current production scenario. There is evidence supporting it is plausible that following an update in the cast design, the amount of disc burrs at the EDC facility as well as the risk of trapping air bubbles during the coating operations are reduced.
- ***H2*** - Contributing factors to the Machining manufacturing step.
  - ***H2.a****: The sequence of machine operations in each of the LiCON centers has an influence on the overall performance of the LiCON cell.* - **VERIFIED**

    Section 7.3.4 provides strong evidence that the sequence of machine operations is crucial in determining whether disc burrs and certain chip types are present in the machined part.
  - ***H2.b****: The choice of tooling in each of the LiCON centers has an influence on the overall performance of the LiCON cell.* - **PLAUSIBLE**

    Choice of tooling has not been directly tested as it eludes from the objectives of this report. There is evidence supporting it is plausible that different tools (utilized with appropriate cutting data) can reduce the cycle time, limit the presence of unwanted burrs or chips, and otherwise improve machining operations.
- ***H3*** - Effect of external implementations.
  - ***H3.a****: How the machined parts are handled has a direct implication on the operations conducted in the EDC coating facility.* - **VERIFIED**

There is strong support suggesting that the way parts are handled (by the robotic arms, after the machining operations are completed) has a direct impact on the volume of chips recorded at the EDC facility and the presence of disc burrs. Not only that, but this also contributes to recording fewer failures at later stages of the manufacturing process.

  - ***H3.b***: *How the machined parts are addressed by the compressed air fixtures (CAF) has a direct implication on the operations conducted in the EDC coating facility.* - **VERIFIED**

    The reviewed CAF design is capable of removing all chips present on the machined components, known to cause problems throughout the manufacturing sequence of the 22" brake calipers.

- ***H4*** - Effect on downstream processes. - **VERIFIED**
  Following implementations in the LiCON cell, fewer problems have been encountered in processes following the ED coating, as visible in figure 7.2.

In conclusion, these chip and burr management techniques are applicable to most industries with some modification. Any solution regarding handling or compressed air fixtures does however require a tailored approach to the component in question. The transition to an external CAF (rather than internal flushing operations) has proven to be pivotal in making efficient use of personnel and equipment. Development of tool exit geometries can also be employed wherever disc burrs are problematic. Exit geometries are a widely applicable solution that can be developed further; nevertheless, the results attained in this study suggest improvements in the formation behavior that can be utilized in future research or industries alike. Similarly, less prominent disc burrs are achievable by reducing the feed rate in the range $h_{1min} < h_1 < \varepsilon_{III}$. On the other hand, a theoretical framework dictating the optimum chip thickness is absent and constitutes a topic in need of future research.

8 Conclusion

In conclusion, the efficient and sustainable management of chips and burrs during machining operations is of paramount importance for modern manufacturing processes. This study has provided a thorough overview of the chip carryover phenomenon, its implications on downstream processes, and potential solutions to minimize its impact on production. The proposed strategies have been based on empirical findings and a hypotheses-based framework, which allowed for a quantitative assessment of their cost benefit. By addressing this aspect of machining operations, manufacturers can achieve significant improvements in material and energy resource use, as well as in product quality standards.

One of the main challenges in chip management is the presence of burrs and chips trapped in internal cavities, which can result in costly re-manufacturing or scrapping of significant portions of produced volume. Effective planning for chip management strategies are therefore crucial to avoid these problems. This study has shown that a thorough understanding of chip and burr formation behavior can help identify particularly problematic chips and burrs that can be addressed by changes in cutting parameters or workpiece geometry. The proposed solutions have been shown to be effective in reducing cycle time and improving product quality, while also contributing to a more sustainable and cost-effective production process.

Peripheral solutions such as compressed air fixtures or tailored sequences of motions can also be employed to efficiently remove internal and external chips. However, the choice of solution should be tailored to the specific component or workpiece being addressed, as different geometries may require different approaches. Implementing the proposed strategies can therefore result in increased complexity and reduced flexibility in the machining sequence, but the potential benefits in terms of economic and environmental sustainability make it a worthwhile trade-off.

Overall, the findings of this study highlight the importance of a broad and cross-functional approach to the development and implementation of improved production strategies. By addressing the issue of chip carryover in a holistic manner, manufacturers can achieve significant improvements in material and energy resource use, as well as in product quality standards. The proposed solutions can be adapted to different contexts and their potential cost benefits can guide decision-making towards achieving optimal results. The future of sustainable manufacturing processes relies on the adoption of such strategies, and this study provides a valuable contribution to this ongoing effort.

References

ACEA, The European Automobile Manufacturers' Association (2022). *Trucks: what they are and why they are so important.* URL: https://www.acea.auto/fact/trucks-what-they-are-and-why-they-are-so-important/ (visited on 07/03/2023).

Agmell, Mathias (2011). *ShortCut project.* Lund University.

Agmell, Mathias, Aylin Ahadi, Oleksandr Gutnichenko, and Jan-Eric Ståhl (2017). "The influence of tool micro-geometry on stress distribution in turning operations of AISI 4140 by FE analysis". In: *The International journal of advanced manufacturing technology* 89.9, pp. 3109–3122.

Andersson, Mats and Jan-Eric Ståhl (2007). "Polar machinability diagrams—a model to predict the machinability of a work material". In: *Sweden production symposium. Göteborg.*

Angelakoglou, K. and G. Gaidajis (2015). "A review of methods contributing to the assessment of the environmental sustainability of industrial systems". In: *Journal of Cleaner Production* 108, pp. 725–747. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2015.06.094. URL: https://www.sciencedirect.com/science/article/pii/S0959652615008276.

Aurich, Jan C, David Dornfeld, PJ Arrazola, V Franke, L Leitz, and S Min (2009). "Burrs—Analysis, control and removal". In: *CIRP annals* 58.2, pp. 519–542.

Bikerman, J.J (1947). "The fundamentals of tackiness and adhesion". In: *Journal of Colloid Science* 2.1, pp. 163–175. ISSN: 0095-8522. DOI: https://doi.org/10.1016/0095-8522(47)90017-2. URL: https://www.sciencedirect.com/science/article/pii/0095852247900172.

Bil, Halil, S Engin Kılıç, and A Erman Tekkaya (2004). "A comparison of orthogonal cutting data from experiments with three different finite element models". In: *International Journal of Machine Tools and Manufacture* 44.9, pp. 933–944.

Chungchoo, C and D Saini (2002). "A computer algorithm for flank and crater wear estimation in CNC turning operations". In: *International Journal of Machine Tools and Manufacture* 42.13, pp. 1465–1477.

Delmas, Magali and Vered Doctori Blass (2010). "Measuring corporate environmental performance: the trade-offs of sustainability ratings". In: *Business Strategy and the Environment* 19.4, pp. 245–260.

Döbbeler, Benjamin and Fritz Klocke (2017). "Process Oriented Choice of Lubricant Pressure and Volume Flow to Increase Machining Process Efficiency". In: *Procedia Manufacturing* 8, pp. 361–368.

Dornfeld, DA, JS Kim, H Dechow, J Hewson, and LJ Chen (1999). "Drilling burr formation in titanium alloy, Ti-6AI-4V". In: *CIRP annals* 48.1, pp. 73–76.

Elkington, John (2013). "Enter the triple bottom line". In: *The triple bottom line: Does it all add up?* Routledge, pp. 1–16.

Ernst, H (1938). "Physics of metal cutting, Symposium of machining of metals". In: *Trans. American Society of Metals* 1.

Eurostat (2016). "RAMON—Reference And Management of Nomenclatures [SECTION XVII - VEHICLES, AIRCRAFT, VESSELS AND ASSOCIATED TRANSPORT EQUIPMENT]". In: URL: https://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=DSP_NOM_DTL_VIEW&StrNom=CN_2022&StrLanguageCode=EN&IntPcKey=&IntKey=49566535&StrLayoutCode=HIERARCHIC&IntCurrentPage=1.

Gillespie, LaRoux K (1973). "The formation and properties of machining burrs". In.

Groover, Mikell P (2020). *Fundamentals of modern manufacturing: materials, processes, and systems*. John Wiley & Sons.

Haldex (Mar. 2022). *Haldex, 2021 Annual Report with Sustainability Report*. Tech. rep.

Hallock, MF, TJ Smith, SR Woskie, and SK Hammond (1994). "Estimation of historical exposures to machining fluids in the automotive industry". In: *American journal of industrial medicine* 26.5, pp. 621–634.

Harvey, L.D. Danny (2021). "Iron and steel recycling: Review, conceptual model, irreducible mining requirements, and energy implications". In: *Renewable and Sustainable Energy Reviews* 138, p. 110553. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2020.110553. URL: https://www.sciencedirect.com/science/article/pii/S1364032120308376.

Jawahir, IS (1988). "The chip control factor in machinability assessments: recent trends". In: *Journal of Mechanical Working Technology* 17, pp. 213–224.

Jung, Jinhyuk and Jun Ni (2003). "Prediction of coolant pressure and volume flow rate in the gundrilling process". In: *J. Manuf. Sci. Eng.* 125.4, pp. 696–702.

Köhler, Jens (2014). "Cutting Edge Geometry". In: *CIRP Encyclopedia of Production Engineering*. Ed. by Luc Laperrière and Gunther Reinhart. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 294–299. ISBN: 978-3-642-20617-7. DOI: 10.1007/978-3-642-20617-7_6398. URL: https://doi.org/10.1007/978-3-642-20617-7_6398.

Leitz, L, V Franke, and JC Aurich (2010). "Burr formation in drilling intersecting holes". In: *Burrs-Analysis, Control and Removal: Proceedings of the CIRP International Conference on Burrs, 2nd-3rd April, 2009, University of Kaiserslautern, Germany*. Springer, pp. 99–105.

Lindeke, Richard R, AJ Atherton, and FC Schoenig (1995). "Improved hole making experiences with very high pressure lubricating coolants delivered through twist drills". In: *Technical Papers-Society of Manufacturing Engineers-All Series*.

López de Lacalle, LN, J Pérez-Bilbatua, JA Sánchez, JI Llorente, A Gutierrez, and J Albóniga (2000). "Using high pressure coolant in the drilling and turning of low machinability alloys". In: *The International Journal of Advanced Manufacturing Technology* 16.2, pp. 85–91.

Lotfi, Mohammad, Ali Akhavan Farid, and Hamid Soleimanimehr (2015). "The effect of chip breaker geometry on chip shape, bending moment, and cutting force: FE analysis and experimental study". In: *The International Journal of Advanced Manufacturing Technology* 78.5, pp. 917–925.

Manjunathaiah, Jairam and William J Endres (2000). "A new model and analysis of orthogonal machining with an edge-radiused tool". In: *J. Manuf. Sci. Eng.* 122.3, pp. 384–390.

McFarlane, Jo S and David Tabor (1950). "Adhesion of solids and the effect of surface films". In: *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* 202.1069, pp. 224–243.

Merchant, M Eugene (1945). "Mechanics of the metal cutting process. I. Orthogonal cutting and a type 2 chip". In: *Journal of applied physics* 16.5, pp. 267–275.

Milosan, Ioan (2014). "The manufacturing of a special wear-resistant cast iron used in automotive industry". In: *Procedia-Social and Behavioral Sciences* 109, pp. 610–613.

Min, Sangkee (2001). *Modeling of drilling burr formation and development of expert system.* University of California, Berkeley.

Min, Sangkee, David A Dornfeld, and Yohichi Nakao (2003). "Influence of exit surface angle on drilling burr formation". In: *J. Manuf. Sci. Eng.* 125.4, pp. 637–644.

Nakayama, Kazuo (1962). "A study on chip-breaker". In: *Bulletin of JSME* 5.17, pp. 142–150.

Ogawa, Makoto and Kazuo Nakayama (1985). "Effects of chip splitting nicks in drilling". In: *CIRP Annals* 34.1, pp. 101–104.

Orłowicz, AW, M Mróz, Miroslaw Tupaj, and A Trytek (2015). "Materials used in the automotive industry". In: *Archives of foundry engineering* 15.

Reynolds, Osborne (1886). "IV. On the theory of lubrication and its application to Mr. Beauchamp tower's experiments, including an experimental determination of the viscosity of olive oil". In: *Philosophical Transactions of the Royal Society of London* 177, pp. 157–234. DOI: 10.1098/rstl.1886.0005. eprint: https://royalsocietypublishing.org/doi/pdf/10.1098/rstl.1886.0005. URL: https://royalsocietypublishing.org/doi/abs/10.1098/rstl.1886.0005.

Roman, Dan (2018). "Safety outside the box: Going beyond the standard specific to your equipment". In: *2018 IEEE Symposium on Product Compliance Engineering (ISPCE).* IEEE, pp. 1–4.

Seco Tools, AB (2021). *Product detail – Inserts Carbide chipbreakers.* Seco Tools, p. 111. URL: https://www.secotools.com.

— (2023). *Product detail – Spot Facing Cutters.* Seco Tools, pp. 798–799. URL: https://www.secotools.com.

Shokrani, Alborz, Vimal Dhokia, and Stephen T Newman (2012). "Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids". In: *International Journal of machine Tools and manufacture* 57, pp. 83–101.

Sreejith, PS and Bryan Kok Ann Ngoi (2000). "Dry machining: machining of the future". In: *Journal of materials processing technology* 101.1-3, pp. 287–291.

Ståhl, Jan-Eric (2011). "The development of NEXT STEP beyond Lean Production - The link between technology and economics with focus on sustainable developments". English. In: Keynote speech; 2011 International Conference on Applied Mechanics, Materials and Manufacturing ; Conference date: 18-11-2011 Through 20-11-2011.

Ståhl, Jan-Eric and AB Seco Tools (2012). *Metal cutting theories and models*. Division of Production and Materials Engineering.

Ståhl, Jan-Eric and Christina Windmark (2021). *Sustainable Production Systems: The Link Between Technology and Economy with a Global Perspective*. Production and Materials Engineering, Lund University.

Ståhl, Jan-Eric et al. (2024). "Skärande bearbetning i teori och praktik, ett samarbete mellan författarna SECO Tools och Studentlitteratur AB". During final editing with expected release in 2024.

Toropov, Andrey and Sung-Lim Ko (2007). "Prediction of shear angle for continuous orthogonal cutting using thermo-mechanical constants of work material and cutting conditions". In: *Journal of materials processing technology* 182.1-3, pp. 167–173.

WCED, Special Working Session (1987). "World commission on environment and development". In: *Our common future* 17.1, pp. 1–91.

Yan, Pei, Yiming Rong, and Gang Wang (2016). "The effect of cutting fluids applied in metal cutting process". In: *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 230.1, pp. 19–37.

Yılmaz, Bahattin, Şener Karabulut, and Abdulkadir Güllü (2020). "A review of the chip breaking methods for continuous chips in turning". In: *Journal of Manufacturing Processes* 49, pp. 50–69.

List of Figures

List of Tables

Appendices

Appendix A: Manufacturing Cost

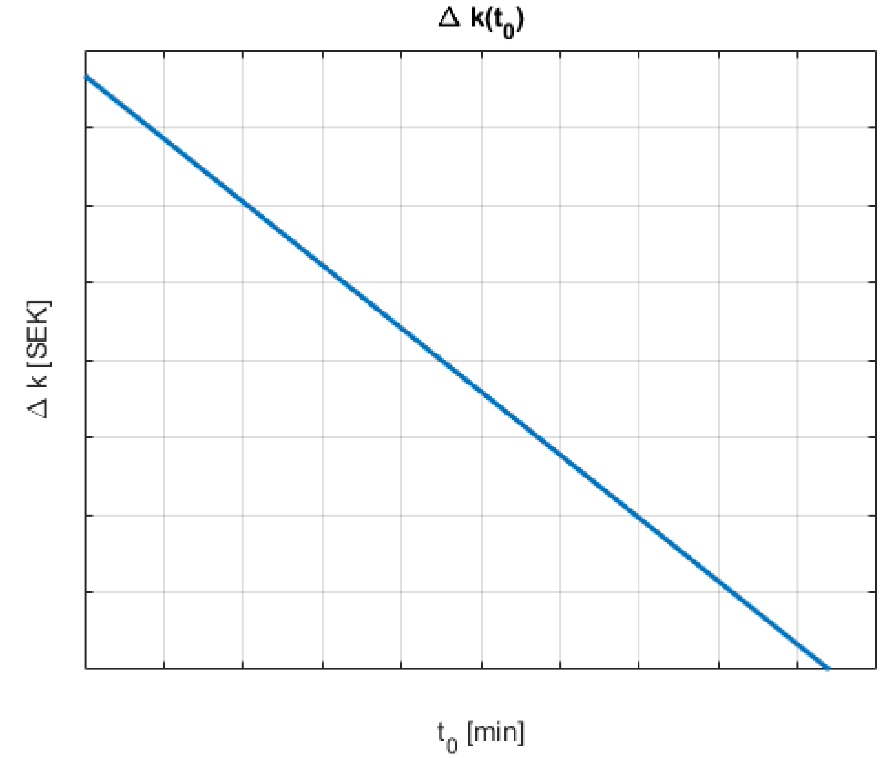


Figure A.1: Reduction on part cost ($\Delta k(t_0)$).

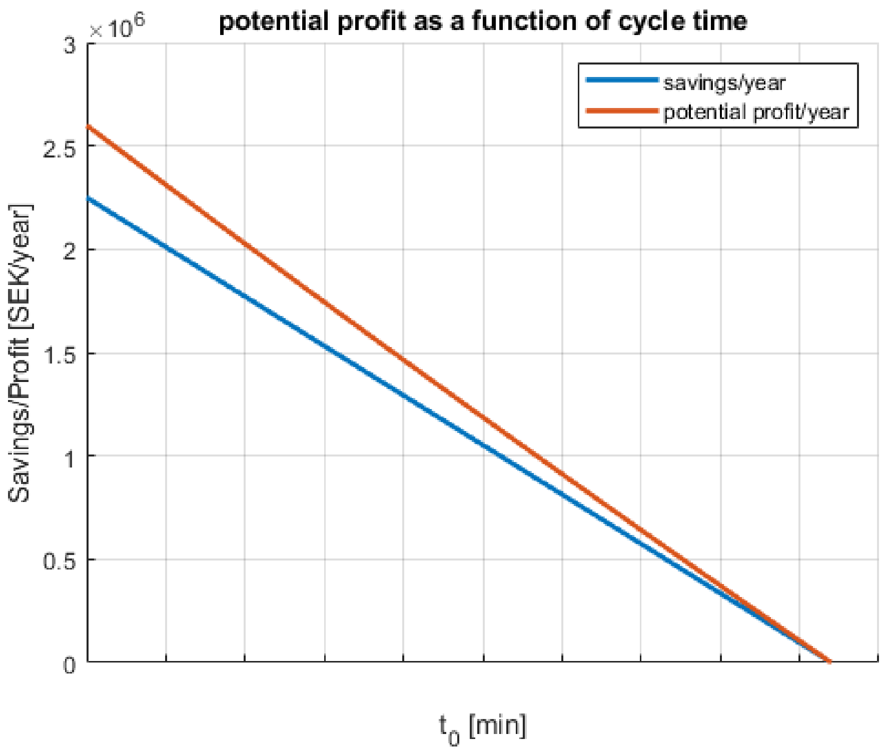


Figure A.2: Potential profit as a function of cycle time reduction.

Matlab script

```
clear all, close all, clc
KB = -;                            % Material cost
n = -;                             % Operators
p = -;                             % Interest rate
ni = -;                            % Investment lifespan (yrs)
nm = -;                            % Number of machines
af = (p*(1+p)^ni)/((1+p)^ni-1);    % Annuity factor
Kinv = -;                          % Hourly investment cost of cell
KAt = -;                           % Yearly tool cost 22' /machine
qQ = -;                            % Rejects ratio
qs = -;                            % Downtime ratio
qp = -;                            % Reduced prod. pace
Q = -;                             % Yearly prod volume 22 (incl. failures)
kA = -;                            % Tool cost/part
Kps = -;                           % Yearly total (Prof. serv.)/machine
kps = -;                           % Average hourly cost of "Professional services"
KG = -;                            % Yearly total (other) /machine
kG = -;                            % Average hourly cost of "Other consumption".
KCP = -;                           % Cost of machines during operation
KCS = -;                           % Cost of machines during standstill
Km = -;                            % Yearly cost of maintenance 22'
km = -;                            % Maintenance cost/part
KD = -*n;                          % Hourly cost of personell (total)
No = -;                            % Nominal batch size
tor = -;                           % Original cycle time
t1 = -;                            % Cycle time (-1/100 for loop)
Tsu = -;                           % Setup time
Tp = -;                            % Total production time
URP = -;                           % Production capacity utilization rate
M = -;                             % Current profit margin
for  i=1:1:(tor-t1)*100
    to(i) = t1+i/100;
    Bb = (KB/No)*(No/(1-qQ));
    Bcp = (KCP/(60*No))*((to(i)*No)/((1-qp)*(1-qQ)));
    Bcs = (KCS/(60*No))*(((to(i)*No*qs)/((1-qQ)*(1-qs)*(1-qp)))+Tsu+((1-URP)/URP)*Tp);
    Bd = (KD/(60*No))*(((to(i)*No)/((1-qQ)*(1-qs)*(1-qp)))+Tsu+((1-URP)/URP)*Tp);
    k(i) = Bb+Bcp+Bcs+Bd+km;
    Dk(i) = k(i)-k(1);
    DK(i) = Dk(i)*Q*nm;            % Saving for the cell
end
figure(1)
plot(to(:),flip(Dk(:)), linewidth=2)
grid on, xlabel('t_0 [min]'), ylabel ('\Delta k [SEK]'), title('\Delta k(t_0)')
figure(2), hold on
plot(to(:),flip(DK(:)), linewidth=2)
for i=1:1:(tor-t1)*100
    to(i) = t1+i/100;
    DQ = (to(i)/(t1+0.01))-1;
    P(i) = Q*nm*DQ*(M+Dk(i))+DK(i);
end
plot(to(:),flip(P(:)), linewidth=2),hold on
legend('savings/year','potential profit/year', 'Location', 'northeast')
grid on, xlabel('t_0 [min]'), ylabel ('Savings/Profit [SEK/year]')
title('potential profit as a function of cycle time')
fprintf('\x0394k = %d%s\n', Dk(i), 'SEK')
fprintf('\x0394K = %d%s\n', DK(i), 'SEK')
fprintf('Potential profit = %d%s\n', P(i), 'SEK')
```