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Tool Bending: A comparative Study

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Affirmation

This master's thesis report, Tool Bending: A Comparative Study, was written as part of the master's degree work required to obtain a Master of Science with specialization in Production and Materials Engineering at Lund University. All material in this report that is not my own is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

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1. Introduction

Tool bending, or deflection, is a significant problem in machining with solid end mills because it directly causes machining errors, negatively affects surface quality, and can lead to premature tool wear and even tool breakage. Tool bending alters the intended path of the end mill, causing the actual cut to deviate from the programmed trajectory. This results in form errors, dimensional inaccuracy, and poor surface finish, especially critical when machining complex geometries or precision parts [25] [24]. Tool bending in solid end mills occurs due to the combination of high cutting forces, slender tool geometries, and excessive tool sticking lengths. Radial and axial forces during machining cause the end mill to act as a cantilever beam, where even small deflections translate to measurable errors on the workpiece surface [31]. A bent tool increases the risk of chatter, surface roughness, and vibration marks, ultimately raising production costs by requiring more frequent tool changes and potentially scrapping defective parts. Studies show that the selection of machining strategies, tool geometry, and cutting parameters all impact the degree of deflection and associated errors [25].

The master's thesis investigates tool bending in solid carbide end mills during machining of four workpiece materials: CK45 steel (P-group), SS 1.4923 (P-group), SS 316L (M-group), and TiAl₆V₄ (S-group). Five solid end mills (Tool 1 -5) are tested all with 8 mm shank diameter, 40 mm max depth of cut, and 4-5 flutes. Experiments use a CNC milling centre with fixed axial depth of cut (40 mm), radial depth (0.4 mm), and four passes per condition, followed by a spring pass for measurement. Tool bending is measured via surface straightness using a dial gauge at three positions. Tests first vary cutting speed at constant feed (0.05 mm/rev or lower for hard materials), assessing spindle load, sound, and finish. Feed rate is then varied at constant speed, revealing stronger impacts on deflection than speed changes across materials. No coolant for CK45; coolant used for stainless and titanium due to hardness and heat. Results show tools 1,2 and 4 outperform tool 3 and 5 with lower deflection, better finish, and stable cutting; e.g., tool 3 fractured early. Graphs plot deflection vs. speed/feed per material, confirming feed's dominant role and recommending parameter windows, eg: 150-280 m/min at 0.05 mm/rev for TiAl₆V₄. The study concludes feed rate primarily drives bending, aiding tool selection and optimization for precision machining.

Testing in this thesis is intentionally narrow in scope, with a primary focus on the influence of cutting speed and feed during shoulder milling using solid carbide end mills. As a result, other potentially important aspects such as additional cutting parameters, chip formation behaviour, different tool types (e.g. indexable tools), and alternative machining operations (such as slotting, ramping, or drilling) are not addressed. Future work could extend this study by systematically varying further process parameters, analysing chip formation, and including a broader range of tools and machining strategies to build a more comprehensive understanding of tool bending across different cutting conditions.

1.1 Goal Statement

The goal of this master thesis is to develop and test a practical method for evaluating and assessing tool bending in solid carbide end mills, by experimentally studying how feed rate and cutting speed affect deflection in different material groups (P, M and S) and by comparing the behaviour of tools with different designs in terms of tool bending, surface quality, and usable process window.

1.2 Objectives of the Study:

- Investigation of varying cutting speed and feed rate and their influence on tool bending in solid carbide end mills, which of the two holds a stronger influence on tool bending.
- To create and test a practical setup for accurately measuring tool bending in solid carbide end mills during real machining tests.
- To perform a comparative analysis of solid carbide end mills of different designs under identical cutting conditions, evaluating variations in tool bending, surface quality, and machining performance.

2. Literature Review

2.1 Tool Bending

2.1.1. Background

Tool bending, also referred to as tool deflection, is the elastic deformation of the cutting tool under the cutting forces experienced during machining. It occurs primarily due to mechanical loads, the combination of cutting forces and moments, acting on the tool. Research shows that tool bending increases with increased cutting forces, tool length, decreased tool rigidity, and due to wear on the cutting edge [21]. Tool bending negatively impacts dimensional accuracy and surface finish of machined parts, as the actual cutting-edge position differs from the intended tool path due to elastic deformation. Deflection-induced inaccuracies result in oversize components, poor tolerances, and increased scrap or rework rates [21]. Tool bending is caused primarily by side or radial cutting forces acting on the unsupported length of the tool, generating a bending moment proportional to the applied force and the distance from the support point [22]. The magnitude of deflection depends on tool geometry, material properties, axial/radial engagements, and cutting parameters such as feed and speed [23]. Excessive tool bending can result in poor surface quality, loss of dimensional control, increased tool wear, and even tool breakage [24]. Strategies such as optimizing tool path (e.g., using zig-zag strategies with minimal cutter engagement), reducing overhang, using stiffer tools, and selecting optimal parameters have been shown in research to reduce deflection [25]. Advanced CAD/CAM and simulation-based approaches now allow for real-time prediction and compensation of tool bending in complex geometries and sensitive materials [25].

2.1.2 Causes of Tool Bending

Cutting forces, tool geometry, material properties, and cutting conditions each have a critical impact on tool bending during machining.

Causes	Description	Score
Cutting or forming forces	Lateral/radial cutting forces generated by feed, depth of cut, and workpiece hardness create bending moments on the overhanging part of the end mill and are identified as the primary driver of tool bending [42].	5
Material properties	Tool material stiffness (Young's modulus) and toughness determine how much it will elastically bend under a given force, carbide tools deflect less than HSS for the same loading, and all tools in the study are solid carbide with similar stiffness.	3
Unsupported length (overhang)	The length of tool protruding from the holder relative to its diameter governs bending according to cantilever/beam theory; larger length-to-diameter ratios lead to much higher deflection for the same load [30][41].	4
Tool Geometry	Geometric features such as rake and clearance angles alter both the magnitude and direction of cutting forces. For example, a larger rake angle can reduce cutting force but may also reduce tool stiffness and increase deflection under specific conditions. The number of flutes, their orientation, and cutting-edge profile affect chip load distribution, influencing the directions and magnitudes of bending during a cut [43] [44].	3
Improper clamping or setup	Inadequate tool or workpiece clamping, or poor fixturing, increases effective unsupported length and compliance, raising bending and vibration risk beyond what beam theory for the bare tool would predict [30].	3
Thermal effects	Heat from cutting can reduce tool and workpiece stiffness locally, alter cutting forces (via thermal softening), and promote wear, all of which can increase tool deflection; coolant use for stainless steels and TiAl ₆ V ₄ in the tests is partly to manage this [30].	3
Workpiece material (indirect cause)	Harder and more difficult-to-machine materials (SS 1.4923, SS 316L, TiAl ₆ V ₄) generate higher cutting forces and temperatures, leading to greater bending at similar cutting data compared to CK45.	4

Table 2.1 Causes of Tool Bending

Score – 1-Very low, 2-Low, 3-Medium, 4-High, 5-Very High

2.1.3. Effects of Tool Bending

Effect	Description	Importance
Dimensional Inaccuracy	Tool bending shifts the tool path, causing deviations in the machined parts dimensions and geometries. [35]	5
Surface Finish Deterioration	Deflection leads to surface waviness or chatter, reducing part quality [34].	4
Tool Wear	Uneven or excessive tool loading accelerates wear and potential tool breakage [34].	4

Table 2.2 *Effects of Tool Bending*

2.1.4. Previous Studies and Solutions

Early models treat the tool as a cantilever beam and calculate deflection by applying beam theory, where cutting forces (assumed concentrated or distributed) cause elastic bending. The main limitation is that these models simplify the load distribution and may not capture dynamic or three-dimensional effects in real operations [30] [41]. Mechanistic models improve prediction by computing instantaneous cutting forces along the cutting edge, allowing for distributed loading and greater realism in the calculated deflections [41].

FEM has become a leading method for simulating tool bending, as it can model complex tool geometries and simulate how distributed, time-varying forces cause three-dimensional elastic deformation. FEM models are validated experimentally and show good correlation with measured tool tip deflections and stress patterns. Recent FEM-based studies incorporate the effect of varying cutting parameters, tool wear, and real engagement areas, resulting in more accurate predictions of bending under practical machining conditions [30] [41].

State-of-the-art approaches integrate cutting force models and FEM-based deformation into a single simulation framework, streamlining calculation and enabling real-time or

near-real-time predictions for process optimization. These models can be embedded into digital twins and CNC control algorithms for adaptive compensation of tool deflection during high-precision machining [41]. Experimental validation, using dynamometers, laser sensors, and high-resolution displacement measurement, is routinely bundled with modelling to ensure accuracy and repeatability [32] [41]. Some research combines analytical, numerical, and machine vision/image processing methods to directly measure or infer deflection during cutting, enabling in-situ validation of modelling predictions [32].

Reviews and case studies consistently report that tool bending is a substantial source of geometric error in precision machining, and that modelling advances especially with FEM have enabled effective process parameter optimization, tool selection, and improved part accuracy [30]. State-of-the-art modelling allows process engineers to minimize deflection by optimizing tool geometry, material selection, and process parameters in a predictive, data-backed manner [41].

2.1.5 Minimizing Tool Bending

Multiple advanced technologies and methods have been developed to minimize or control tool bending in machining. Effective strategies focus on optimizing cutting parameters, tool geometry, toolpath planning, and real-time compensation via modelling and feedback systems

Adjusting feed rate, cutting speed, and depth of cut significantly impacts tool bending. Increasing feed rate within safe limits can reduce unwanted surface irregularities associated with excessive bending, as shown in micro-milling studies employing predictive modelling for parameter selection [45]. Decreasing tool overhang (projection from the holder) is a widely recommended physical intervention, with research indicating that a 20% reduction in overhang can cut deflection by more than half [46]. Using stiffer tool holders, larger tool diameters, and tools with shorter length-to-diameter ratios are practical geometric solutions adopted in industry and referenced in academic work [47].

Real-time toolpath correction based on predicted or measured deflection is employed: equivalent diameter cantilever beam models and feedback mechanisms can correct the toolpath in response to detected deflection forces [31]. Mechanistic and empirical modelling, integrating direct or indirect measurement of cutting forces, enables continuous compensation for elastic tool displacement, thereby maintaining machining accuracy [49]. Use of multi-flute end mills, specialized coatings, and harder tool materials (e.g., carbide, diamond) contributes to both bending and vibration suppression [47]. Adaptive control systems and damping structures in machine tools further reduce vibration-induced bending.

2.2 Basics of metal cutting

2.2.1 Metal Cutting processes

A relative motion between the cutting tool and the workpiece is used to perform a metal cutting operation. The material in front of the cutting tool undergoes significant plastic deformation and stress as the cutting tool moves into the workpiece. The workpiece experiences internal shearing as a result. The removed material flows away in the form of chips. The generated chips often move upwards on the rake face of the tool. Chips that are generated can either be continuous chips, discontinuous chips or chips with a built-up edge based on the type of workpiece material machined. Either a single cutting edge or a multi-edge tool is used throughout the cutting operation. The joint action of various cutting edges occurs in multi-edge operations like milling. The geometric form, the positional accuracy, and the condition of the various cutting edges during the cutting process all affect how much joint action and interference between the actions of the individual cutting edges happens. On the other hand, one example of a single-edged cutting process is turning, which uses just one cutting edge [18] [19].

Cutting processes can be divided into two categories: continuous and intermittent, an example of each is shown in **Fig 2.1**. A cutting edge is periodically engaged and disengaged in sequential steps during intermittent procedures like milling. A cutting edge in a milling operation is only engaged for 50% of the milling tool's rotation. In contrast, continuous processes include turning and boring. Additionally, because the workpiece is dis-continuous, cutting operations that would normally be continuous might be intermittent. For instance, when applied to a workpiece with keyways,

longitudinal turning which is essentially a continuous process becomes intermittent. [18] [19]

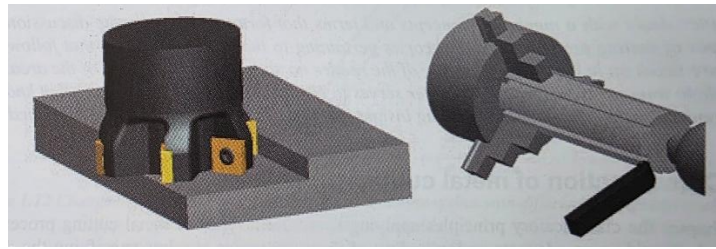


Fig 2.1 Intermittent cutting process, illustrated on the left-hand side and continuous cutting process on the right. [19]

Jan-Eric Ståhl further used three questions/criteria to classify a cutting process in reference to what is said above.

1. Is the basic cutting process continuous or intermittent?
2. Is a single active cutting edge or more than one involved?
3. Is the cutting done in a workpiece having a continuous or a discontinuous surface?

Furthermore, Ståhl devises a principle for cutting process as shown in **fig 2.2**. The basic/general ideology behind is that wear resistance is significantly higher and the heat retention in a cutting tool is significantly lower for a continuous process, alternatively the toughness of a cutting tool and the flexural strength required is much higher for an intermittent process. [19]

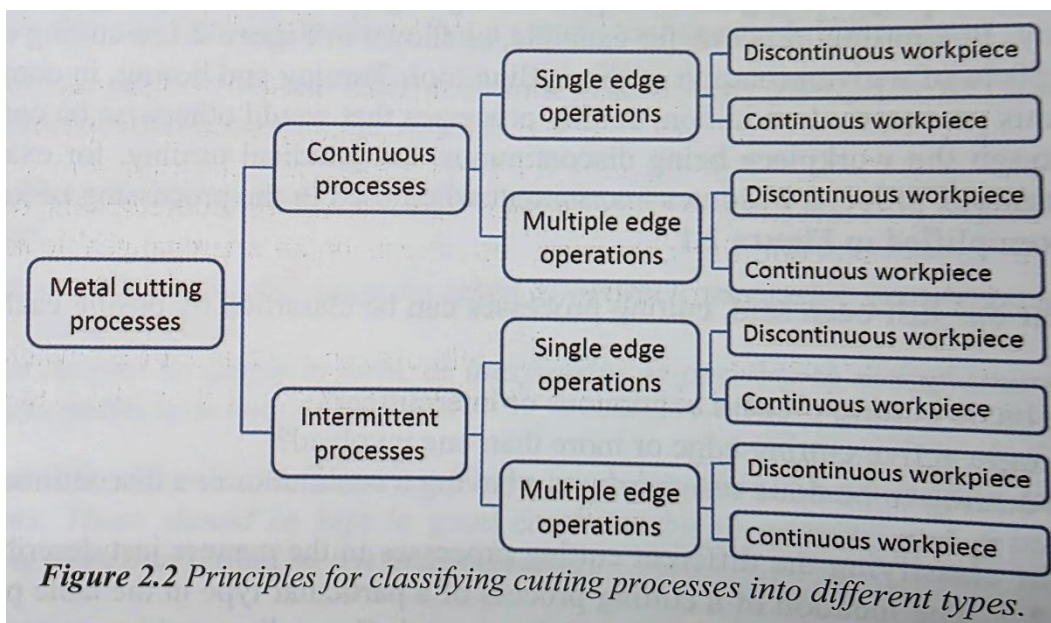


Figure 2.2 Principles for classifying cutting processes into different types.

Fig 2.2 Classification of cutting processes [19]

2.2.2. CUTTING TOOLS

Cutting tools come either as one whole solid block or with indexable inserts for which the most suitable inserts would be used. With continuous usage of these tools wear and tear is a regular phenomenon, however the tools re-machined / re-conditioned once signs of deterioration start to appear. Re- conditioning is done usually by re sharpening the tool or by the preparation of the cutting edge or by applying coating. This process is more commonly seen in a solid cutting tool as compared to a tool that uses an insert. Indexable inserts are attached to a tool holder by clamping, screwing, or some other method. Depending on the type of cutting operation, several terms are used for toolholders. For example, “toolholder” is used for turning, while “milling cutter” is used for milling. [6]

2.2.3 CUTTING PLANES AND DIRECTIONS

Cutting process descriptions consider the planes and directions involved. T, A, and R stand for the three main directions that are orthogonal to one another (T for tangential, A for axial and R for radial direction). When working with rotationally symmetrical workpieces and cutting tools, the T and R directions are utilized. The remaining direction, A, is parallel to the axial center-line of the workpiece or cutting tool and perpendicular to each of the other two directions. [19].

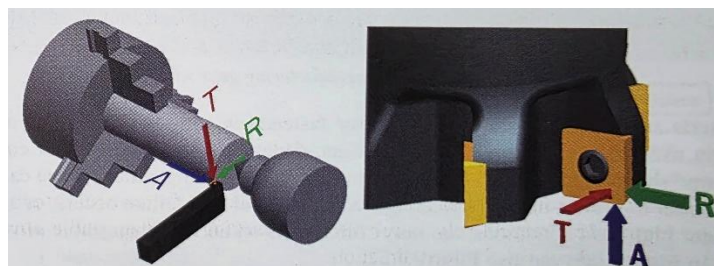


Fig 2.3 T, A and R directions (in case of milling) [19]

2.2.4 CUTTING DATA

The factors used to depict the amount of material removed in a given amount of time are referred to as cutting data. The values chosen for the various factors determine the cutting tool. Below are the different factors used to determine the same.

The speed at which the cutting tool's edge moves across the workpiece surface during cutting is the cutting speed V_c (m/min), representing the tangential velocity at the tool radius. This relative speed governs frictional heating, tool wear, and power consumption, directly impacting material removal rate [51]. The feed rate V_f (mm/min) denotes the linear speed at which the tool advances relative to the workpiece in the machining direction, controlling chip thickness per tooth or revolution. V_f profoundly affects surface roughness, cutting forces, and productivity, with higher values increasing material removal but risking poorer finish and higher loads [52]

The axial or radial movement of the workpiece or the cutting tool during a single rotation of either one, or the distance each one travels in relation to the other within a certain time frame, is represented by the feed f (mm/rev). In some situations, like milling, it can be useful to describe the feed movement in terms of millimetres per minute. The feed per cutting edge or the overall feed of the cutting tool, which is the sum of the feed for each active cutting edge, can be used to characterize feed in multi-edge cutting procedures like drilling and milling. [20]

The measure of workpiece material removed in a single pass of the cutting tool in the axial direction is referred to as the cutting depth A_p (mm) and A_e (mm) is the depth of cut in the radial direction.

There are three basic parameters, theoretical chip thickness H_1 , theoretical chip width b_1 and theoretical chip velocity that apply to a cutting process (**Fig 2.4**). The length of the cutting edge's active section exceeds the cutting depth if the cutting edge's primary direction is not perpendicular to the R-direction. As a result, the cutting depth is less than the theoretical chip width b_1 . The primary cutting edge angle k is the angle formed by the cutting edge and the workpiece axis in the A-R plane (**Fig 2.5**). The below set of

equations represents the approximate relationships found between the cutting data and the basic process parameters [19].

$$H_1 = f * \sin k \quad [21]$$

$$B_1 = \frac{Ap}{\sin k} \quad [21]$$

The chip area can be calculated with the below equation

$$A = Ap * f = B_1 * H_1 \quad [19]$$

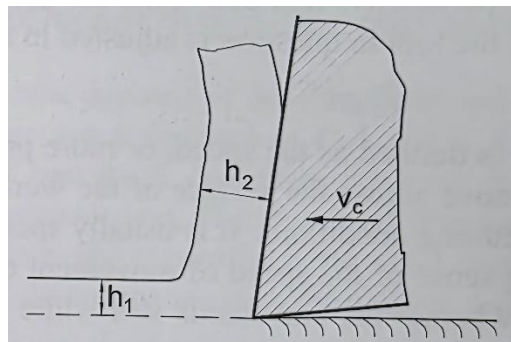


Fig2.4 Basic Parameters of cutting process – theoretical chip thickness h_1 (mm), cutting speed V_c (m/min) [19]

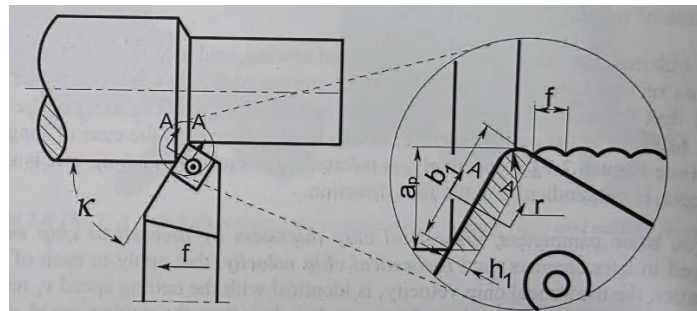



Fig 2.5 Major chip parameters [19]

2.2.5 CUTTING TOOL GEOMETRY

Tool geometry describes the shape and size of a tool; different angles are frequently mentioned in relation to this. It is more challenging to describe a tool geometrically if its form is curved. Advancements in the production of all fundamental kinds of cutting instruments. The microgeometry and macrogeometry of a cutting tool are frequently separated. While its microgeometry mainly focuses on the shape of its cutting edge, or

edge line, its macrogeometry is concerned with its main geometric features. Having the most advantageous cutting tool geometry can be crucial for achieving the desired machining results because of the geometry of a cutting tool that may be involved [18][19].

The included angle and the wedge angle  are two crucial angles. In particular, these two angles have two effects on the cutting tool: a wider wedge angle and a larger included angle provide the cutting edge more strength and improve heat transmission from the cutting edge, which improves cooling by evacuating heat [18][19].

During machining, the cutting tool is subjected to multiple forces resulting from its interaction with the workpiece material. These forces primarily include the main cutting force, feed force, and radial (or thrust) force. The main cutting force acts tangentially to the cutting tool's rotation and is responsible for material removal. The feed force acts in the direction of the feed motion of the tool, and the radial force acts perpendicular to both the cutting and feed forces, pressing the tool against the workpiece [18][19].

Cutting forces are often dependent on machining parameters such as cutting speed, feed rate, depth of cut, tool geometry (rake angle, etc.), tool wear, and lubrication. Cutting forces increase with increasing feed rate and depth of cut because more material is engaged and removed per tool revolution, demanding higher force. Conversely, cutting forces generally decrease with increasing cutting speed due to thermal softening of the workpiece material in the cutting zone [36]. The cutting force components (often F_x , F_y , F_z) are studied in detail. F_y (tangential force) usually has the largest magnitude, followed by F_x (radial) and F_z (feed) forces, although this varies with cutting conditions and tool geometry [37]. Tool geometry such as rake angle directly affects cutting forces; for example, increasing rake angle can reduce cutting forces in some materials, while the opposite trend can be seen in others depending on depth of cut [38]. Cutting forces are measured using dynamometers, such as strain-gauge based tools, to study their real-time variation and provide data for optimizing machining parameters and tool design [38]. The cutting forces have significant effects on tool wear, tool deflection, surface finish, and machining efficiency, making their analysis crucial for process optimization [39]. Lubrication and cooling methods such as nano-lubricants can reduce cutting forces by lowering friction and temperature in the cutting zone [40].

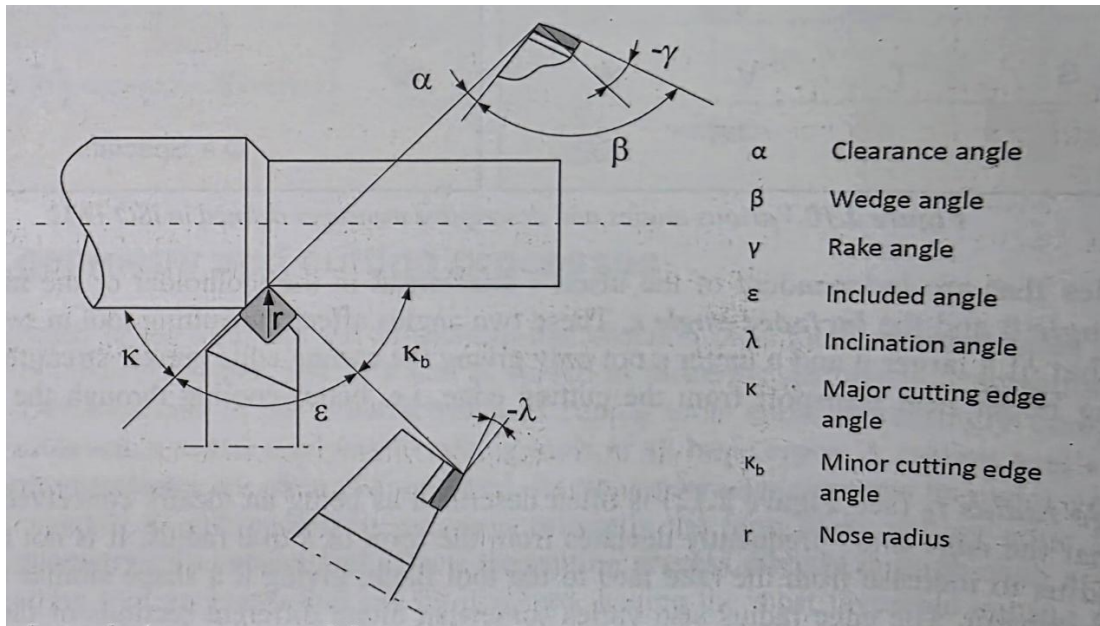


Fig 2.6 Angular and other geometrical designations [19]

2.2.6 Solid End Mills WRT to Milling

Solid end mills are essential cutting tools in precision milling, widely researched for their design, performance, and optimization in various machining operations. Research papers provide in-depth analysis of their material composition, geometry, manufacturing methods, and application to different workpiece materials. Solid end mills are often made from high-speed steel (HSS), carbide, cobalt alloys, or advanced ceramics. Carbide end mills, in particular, have been studied extensively for their superior hardness, heat resistance, and performance in high-speed applications, including the milling of materials like TiAl₆V₄ and Al7075-T6. Research confirms that carbide end mills retain their sharpness longer and allow for higher cutting speeds compared to HSS, making them more suitable for machining hard materials [26] [27]. Academic studies highlight that the geometry of solid end mills such as helix angle, flute design, and end cutting edge configuration directly impacts cutting efficiency, tool life, and surface finish. Advanced simulation and optimization techniques (e.g., finite element analysis) are used to predict and enhance end mill performance under varying cutting conditions, as well as to reduce thermal and mechanical stresses during high-speed milling. Custom designs with variable helix or segmented unequal helical angles

are researched to mitigate chatter and improve machining stability. [28] [29]. Solid end mills are evaluated based on their performance in machining difficult-to-cut alloys and composites, such as titanium alloys and hardened steels. Research papers analyse machinability, tool wear, cutting force, and surface integrity under diverse machining parameters. Relevant studies use experimental and numerical methods to correlate process variables (cutting depth, feed per tooth, speed) with tool stress and lifetime [26] [27].

3. Experimental Setup and Methodology

3.1 Cutting Tools

In the project a total of 5 different solid end mills has been used. The performance of these tools has been observed. Tools 1, 2 and 3 have 4 flutes. Tools 4 and 5 have 5 flutes each.

3.1.1. Tool 1

This is a solid end mill made from carbide. It has a cylindrical shank with a shank diameter of 8mm. It has a total of 4 cutting edges with a cutting diameter of 8mm. The maximum depth of cut in the direction of feed is 40mm. Further data is shown in **Table 3.1**.

NAME	DESCRIPTION	VALUE
APMXS	Depth of cut in feed direction	40 mm
CCC	Center cutting capability	-1
CHW	Corner chamfer width	0.1 mm
Coating	Cutting tool coating	NXT
CSP	Coolant supply property	No internal coolant
DC	Cutting Diameter	8.0 mm
DMM	Shank Diameter	8.0 mm
FCEDC	Face Cutting Edge Count	4
FHA	Flute Helix Angle	48 Degree
KCH	Corner Chamfer Angle	45 Degree
OAL	Overall Length	85 mm
PCEDE	Peripheral Cutting Edge Count	4
PSIR	Tool Lead Angle	0 Degree
Shank Type	Shank shape	Cylindrical
TCDMM	Shank Diameter Tolerance Class	H5
Weight	Net Weight	0.055 KG

Table 3.1 Cutting Parameters for Tool 1 [49]

3.1.2 Tool 2

This is also a solid end mill made from carbide with cutting parameters similar to the above-mentioned tool except with a change. It has a landing of 1° . This refers to a taper or draft angle on the cutting portion of the end mill. This provides an option to machine a given surface at a tapered angle. For example, while using the milling tool to perform an operation of shoulder milling the angle made at the shoulder would be 89° and not 90° . This can be often used for molds, dies and parts that need easy removal from molds.

This tool comes with a cylindrical shank with a shank diameter of 8mm. The maximum depth of cut along the direction of feed is 40mm. The peripheral cutting edge count is 4 with a

maximum cutting diameter of 8mm. However, this milling tool is a prototype developed exclusively for R&D purpose and not yet available in the market for sale. **Table 3.2** shows a broader data.

NAME	DESCRIPTION	VALUE
APMXS	Depth of cut in feed direction	40 mm
CCC	Center cutting capability	-1
CHW	Corner chamfer width	0.1 mm
Coating	Cutting tool coating	NXT
CSP	Coolant supply property	No internal coolant
DC	Cutting Diameter	8.0 mm
DMM	Shank Diameter	8.0 mm
FCEDC	Face Cutting Edge Count	4
FHA	Flute Helix Angle	48 Degree
KCH	Corner Chamfer Angle	45 Degree
OAL	Overall Length	85 mm
PCEDE	Pheripheral Cutting Edge Count	4
PSIR	Tool Lead Angle	0 Degree
Shank Type	Shank shape	Cylindrical
TCDMM	Shank Diameter Tolerance Class	H5
Weight	Net Weight	0.55

Table 3.2 Cutting Parameters for Tool 2 [49]

3.1.3 Tool 3

The tool is a solid carbide end mill, specifically a shoulder milling tool designed for advanced and high-performance machining. The shank is cylindrical with a shank diameter of 8mm and a cutting diameter of 8mm. the maximum depth if cut in the direction of feed in 40mm and the cutting-edge count is 4. More information on its cutting data is shown in **Table 3.3**

NAME	DESCRIPTION	VALUE
APMXS	Depth of cut in feed direction	40 mm
Coating	Cutting Tool Coating	NXT
CSP	Coolant supply property	No internal coolant
DC	Cutting Diameter	8.0 mm
DMM	Shank Diameter	8.0 mm
FCEDC	Face Cutting Edge Count	4
FHA	Flute Helix Angle	48 Degree
OAL	Overall Length	63 mm
PCEDE	Pheripheral Cutting Edge Count	4

Table 3.3 Cutting Parameters for Tool 3 [50]

3.1.4. Tool 4

This tool comes with 5 flutes i.e., peripheral cutting edges. This is a solid carbide end mill featuring a cylindrical shank with a diameter of 8mm. It has four cutting edges and a cutting diameter of 8mm. The tool allows for a maximum cutting depth of 40mm in the feed direction. Further information is provided in **Table 3.4**.

NAME	DESCRIPTION	VALUE
APMXS	Depth of cut in feed direction	40 mm
CCC	Center cutting capability	0
CHW	Corner chamfer width	0.1 mm
Coating	Cutting tool coating	NXT
CSP	Coolant supply property	No internal coolant
DC	Cutting Diameter	8.0 mm
DMM	Shank Diameter	8.0 mm
FCEDC	Face Cutting Edge Count	5
FHA	Flute Helix Angle	48 Degree
KCH	Corner Chamfer Angle	45 Degree
OAL	Overall Length	85 mm
PCEDE	Pheripheral Cutting Edge Count	5
PSIR	Tool Lead Angle	0 Degree
Shank Type	Shank shape	Cylindrical
TCDMM	Shank Diameter Tolerance Class	H5
Weight	Net Weight	0.063 KG

Table 3.4 Cutting Parameters for Tool 4 [49]

3.1.5. Tool 5

This is a solid carbide end mill with 5 cutting edges with a cylindrical shank and a shank diameter of 8mm. The maximum cutting diameter is 8mm. Maximum depth of cut in the direction of feed is 40mm. A detailed specification is given in **Table 3.5**.

NAME	DESCRIPTION	VALUE
APMXS	Depth of cut in feed direction	40 mm
CCC	Center cutting capability	0
CHW	Corner chamfer width	0.5 mm
Coating	Cutting tool coating	AlTiN
CSP	Coolant supply property	No internal coolant
DC	Cutting Diameter	8.0 mm
DMM	Shank Diameter	8.0 mm
FCEDC	Face Cutting Edge Count	5
FHA	Flute Helix Angle	48 Degree
KCH	Corner Chamfer Angle	45 Degree
OAL	Overall Length	85 mm
PCEDE	Pheripheral Cutting Edge Count	5
PSIR	Tool Lead Angle	0 Degree

Shank Type	Shank shape	Cylindrical
Weight	Net Weight	0.063 KG

Table 3.5 Cutting Parameters for tool 5 [50]

3.2 Workpiece Materials

3.2.1 CK 45 Steel

The CK45 steel is medium carbon steel (0.42-1-0.50%) and has favourable machinability owing to a fair compromise between its strength and ductility in the normalized or annealed state, which ensures a stable cutting regime and predictable tool wear [1]. Studies by Agnieszka Skoczylas, Mariusz Kłonica have shown that the microstructure of normalized CK45, which consists primarily of ferrite and pearlite, facilitates machining processes by providing a relatively uniform and softer matrix compared to fully hardened steels [2]. The use of coated carbide tools on CK45 improves wear resistance in milling applications, extending the tool life compared to uncoated tools. Surface treatments on CK45, such as laser hardening, also impact tool wear by increasing surface hardness and affecting chip formation [1] [2]. Tool life studies demonstrate that CK45's machinability is favourable for precision machining tasks, with proper parameter optimization reducing thermal and mechanical loads on the cutting tools [3]. Cutting parameters such as cutting speed and feed have shown to be critical towards tool wear and surface finish. A higher cutting speed has proven to increase surface finish and reduce the cutting forces while depleting the tool life in case of ineffective lubrication. Use of minimum quantity lubrication or nanofluid based coolants have shown to reduce cutting temperature, improves tool life and enhances energy efficiency in machining of CK 45 [4] [5].

3.2.2 SS 1.4923

SS1.4923 is a martensitic stainless steel widely used in high-strength applications. It shares many properties common to martensitic grades which are generally more difficult to machine than ferritic or austenitic stainless steels due to work hardening, higher hardness, and lower thermal conductivity. Research conducted by Shener

Vatansever et al., shows that martensitic stainless steels like SS1.4923 exhibit consistent tool wear behaviour (including flank wear and notch wear) during machining, with tool life and wear characteristics strongly dependent on cutting speed and chip thickness [6]. Tool life models (such as the Colding tool life equation) predict that the optimal cutting speed for longest tool life is around 180 m/min at chip thickness levels below 0.3 mm but decreases at higher removal rates due to increased wear. Hardness of this also plays a vital role in its machinability. SS1.4923 typically has a high hardness range around 45 - 55 HRC in its heat-treated condition, attributed to its martensitic microstructure. Hardness can vary according to processing with values over 50 HRC achievable after quenching and tempering, making it significantly harder than standard carbon steels but providing excellent wear resistance [6]. The hardness contributes to increased wear resistance and strength but also raises machining difficulty, influencing tool wear and cutting forces.

3.2.3 SS 316L

SS 316L is an austenitic stainless steel known for good corrosion resistance and moderate machinability. Machinability varies based on the manufacturing method, microstructure, and surface condition. Studies by authors Abdulmajeed Dabwan , Saqib Anwar, Ali M Al-Samhan, Abdullah AlFaify and Mustafa M Nasr show that SS 316L fabricated by processes like laser powder bed fusion (L-PBF) shows varied machinability depending on porosity and layer thickness, affecting cutting forces during milling and turning [7]. The cutting forces during machining vary with part orientation and layer thickness in additive manufactured 316L, with lower porosity samples showing more uniform forces and better machinability [7]. Research by Aby M. Philip, Kalyan Chakraborty indicate dry turning and milling of ss316L Dry turning and milling studies reveal SS 316L generates built-up edges on cutting tools, requiring optimization of cutting speeds and feeds to minimize tool wear and surface roughness [8]. Hardness of SS 316L depends on fabrication and treatment. Typical Vickers hardness (HV0.1) ranges between 150 and 250 HV depending on processing. Wrought SS 316L generally shows hardness around 150 HV. Additively manufactured (SLM or L-PBF) samples often exhibit higher hardness values in the range of 220–250 HV, attributed to finer microstructure from rapid solidification [9] [10]. Heat treatments and

post-processing like shot peening can increase hardness further by inducing martensitic transformation or grain refinement.

3.2.4 TiAl₆V₄

- TiAl₆V₄ is widely used for aerospace, biomedical, and automotive applications due to its excellent strength-to-weight ratio and corrosion resistance. However, it is a difficult-to-machine alloy due to its low thermal conductivity, low elastic modulus, high strength, chemical reactivity, and hardness [11] [12]. The alloy maintains high hardness even at elevated temperatures, which increases cutting forces, results in rapid tool wear, and limits achievable material removal rates during conventional machining [12] [13]. Machining of TiAl₆V₄ is challenging due to high cutting temperatures near the tool – workpiece interface and adhesive/abrasive tool wear mechanisms. Studies on additively manufactured TiAl₆V₄ conducted by Chen Zhang¹ et al., demonstrate, higher hardness and yield strength than wrought materials, leading to higher cutting forces and tool wear, further complicating machining [14]. Use of specialized tool materials (carbide with coatings like TiAlN) and cooling techniques like cryogenic cooling or high-pressure coolant decreases temperature, improving tool life and machinability [12]. The hardness range of TiAl₆V₄ varies with processing; typically, between 320-400 HV, with aged or heat-treated conditions pushing hardness higher due to martensitic or α/β microstructures [15]. Higher hardness in TiAl₆V₄ correlates with increased tool wear, higher cutting forces, and thicker subsurface deformation layers (white layers) after machining, which affect surface integrity and increase burr formation [15]. Hardness impacts machinability considerably, specimens with higher hardness require more cutting power and experience accelerated tool degradation, reducing machining efficiency [16]. Surface hardness also affects fatigue resistance and wear properties of the machined part, linking machining parameters to functional performance of TiAl₆V₄ components [17].

3.3 Experimental Methodology

The present study investigates tool bending behaviour under varying cutting speeds and feeds, while keeping all other machining parameters constant. Four different

workpiece materials were selected to cover a broad spectrum of machinability classes: one from the P group (CK45), two from the M group (SS1.4923 and SS 316L), and one from the S group (TiAl₆V₄). Machining tests were performed using five solid end mills. In addition to characterizing bending behaviour, the study also aimed to perform a comparative evaluation of the cutting tools in terms of their quality and functional performance.

The workpiece material for all trials was prepared as a solid block with dimensions of 300 × 200 × 300 mm. Each block was secured using a vice mounted on the CNC milling center. An initial face milling operation was carried out to eliminate surface rust, scale, and irregularities. The prepared surface maintained an average roughness in the range of 5–10 μm, providing consistent starting conditions for machining. The project also aimed at determining the cutting speeds and feed that would be recommended for these tools.

During the experiments, the axial depth of cut (a_p) was kept constant at 40 mm, while the radial depth of cut (a_e) was fixed at 0.4 mm. The cutting process was executed in two stages:

1. The cutting speed was varied incrementally while keeping the feed rate constant, until the critical operating range of the tool was reached.
2. The feed rate was then varied while holding the cutting speed constant, in order to establish the maximum feed limits sustainable by each tool.

For each set of cutting parameters, two machining passes were performed, and tool bending was subsequently measured using a surface straightness dial gauge. After A machining pass, a spring pass is done to remove as much residual materials on the workpiece as possible with just one pass, testing is continued as long as the value of spring pass is significantly less than its corresponding tool bending measurement. Measurements were taken at three different positions on the machined surface, and the variation across readings was required to remain within a tolerance of 10 μm.

For materials such as stainless steel, which are relatively harder, the maximum allowable value of tool bending was set at 250 microns, while for softer materials, the threshold was established at 200 microns. Additionally, surface finish was considered a critical criterion, a uniform surface finish was required, and the presence of feed marks

or scallop marks was deemed unacceptable, necessitating the termination of the trial if such defects were observed.

Cutting parameters such as speed (N) and table feed (V_f) are calculated using the formulas below

$$V_c = \frac{3.14 * D * N}{1000} \qquad V_f = f * Z * N$$

Where, V_c is the cutting speed (in m/min)

D is the diameter of the tool (in mm)

N is the speed (in rpm)

f is the feed (mm/rev)

Z is the number of flutes

Measured value is Tool Bending in microns.

4. Results and Discussion

4.1 Data Presentation:

4.1.1 Material 1, CK 45 (P-Class)

- For all testing values of A_p (40mm), A_e (0.4mm), no of passes (4) and stock of 1.6mm will remain constant.
- Coolant was not used for this Material.

Tool 1

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
200	0.05	7961	1592	8%	80	10
220	0.05	8757	1752	9%	90	20
230	0.05	9156	1831	9%	100	20
240	0.05	9554	1911	9%	110	20
250	0.05	9952	1990	12%	110	20
280	0.05	11146	2229	14%	110	25

Table 4.1 CK45, Tool 1 Varying Speed

- Smooth cutting, acceptable cutting sound and good surface finish is observed in all the above cases.
- Max speed available on the machine is 12000 rpm, hence testing concludes here.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
200	0.07	7962	2229	9%	110	30
200	0.09	7962	2866	9%	140	40
200	0.11	7962	3503	12%	150	50
200	0.13	7962	4140	12%	180	60
200	0.15	7962	4777	14%	180	70
200	0.17	7962	5414	15%	220	80

Table 4.2 CK45, Tool 1 Varying Feed

- Smooth cutting, acceptable cutting sound and good surface finish is observed in until feed value of 0.15 after which feed marks are observed on the surface of the material.
- Tool bending value of 200 microns is reached, hence testing concludes here.

Tool 2

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
150	0.05	5971	1194	7%	120	40
200	0.05	7961	1592	9%	130	40
220	0.05	8758	1752	11%	160	40
240	0.05	9554	1911	12%	170	50
260	0.05	10350	2070	12%	160	50
280	0.05	11140	2228	14%	160	50

Table 4.3 CK45, Tool 2 Varying Speed

- The max available speed on the CNC machine is 12000 rpm, hence testing concludes here.
- Smooth cutting, acceptable cutting sound and good surface finish is observed in all cases.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
200	0.07	7962	2229	9%	150	40
200	0.09	7962	2866	11%	180	50
200	0.11	7962	3503	12%	210	60

Table 4.4 CK45, Tool 2 Varying Feed

- Tool bending has reached a value of 200 microns i.e., double the initial recommended value. Hence testing concludes here.
- Smooth cutting, acceptable cutting sound and good surface finish is observed in all cases.

Tool 3

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
200	0.05	7961	1592	8%		

Table 4.5 CK45, Tool 3 Varying Speed

- Tool fractures after 2 passes. End of testing for Tool 3. This tool will not be used in any further Machining.

Tool 4

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
200	0.05	7961	1990	9%	90	10
220	0.05	8758	2190	9%	90	20
240	0.05	9550	2387	12%	100	20
260	0.05	10350	2588	12%	100	20
280	0.05	11140	2786	14%	110	30

Table 4.6 CK45, Tool 4 Varying Speed

- Smooth cutting and good surface finish is observed in all the above cases.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
200	0.07	7962	2786	11%	110	30
200	0.09	7962	3583	12%	150	40
200	0.11	7962	4379	14%	170	50
200	0.13	7962	5175	15%	210	60

Table 4.7 CK45, Tool 1 Varying Feed

- Smooth cutting, acceptable cutting sound and good surface finish is observed till 0.11mm value of feed, from this feed marks observed on surface of the workpiece.

Tool 5

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
200	0.05	7962	1990	9%	190	60
220	0.05	8758	2190	9%	190	65
240	0.05	9554	2388	11%	200	70

Table 4.8 CK45, Tool 5 Varying Speed

- For a value of 200 m/min smooth cutting, acceptable cutting sounds and good surface finish is observed.

- For values of 220 m/min and above, abnormal cutting sounds i.e., high pitched sounds are observed along with disturbances in the surface finish.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
200	0.07	7962	2786	12%	240	100

Table 4.9 CK45, Tool 5 Varying Feed

- Smooth cutting, disturbances in the surface finish due to vibrations during machining.

End of CK 45

4.1.2. Material 2, (Stainless Steel) SS 1.4923 (M-Class)

- For all testing values of A_p (40mm), A_e (0.4mm), no of passes (4) and stock of 1.6mm will remain constant.
- Coolant was not used for this material.

TOOL 1

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
150	0.05	5971	1194	7%	80	20
170	0.05	6768	1354	7%	90	20
200	0.05	7962	1592	9%	100	20
220	0.05	8758	1752	9%	100	20
240	0.05	9554	1911	9%	100	25
260	0.05	10350	2070	11%	100	30
280	0.05	11146	2229	12%	110	30

Table 4.10 SS 1.4923, Tool 1 Varying Speed

- Smooth cutting, acceptable cutting sounds and good surface finish observed in all cases.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
150	0.07	5971	1672	7%	110	30

150	0.09	5791	2150	7%	130	40
150	0.11	5791	2627	8%	150	50
150	0.13	5791	3105	9%	170	60
150	0.15	5791	3583	9%	190	70
150	0.17	5791	4060	11%	200	80

Table 4.11 SS 1.4923, Tool 1 Varying Feed

- Smooth cutting, acceptable cutting sound and good surface finish observed till a value of 0.13mm. upon reaching 0.13mm and above disturbances are observed in the surface finish due to vibrations.

TOOL 2

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
150	0.05	5971	1194	7%	140	40
170	0.05	6768	1354	7%	160	50
200	0.05	7962	1592	8%	170	55
220	0.05	8758	1752	9%	170	60
240	0.05	9554	1911	11%	170	60
260	0.05	10350	2070	14%	180	60
280	0.05	11146	2229	15%	190	70

Table 4.12 SS 1.4923, Tool 2 Varying Speed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.
- Since the max available speed on the machine is 12000 rpm, testing concludes here.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
150	0.07	5971	1672	7%	180	50
150	0.09	5971	2150	8%	210	70

Table 4.13 SS 1.4923, Tool 2 Varying Feed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.
- Since tool bending values exceed 200 microns, testing concludes here.

TOOL 4

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
150	0.05	5971	1493	5%	120	20
170	0.05	6768	1692	7%	140	30
200	0.05	7962	1991	8%	140	30
220	0.05	8758	2190	9%	150	40
240	0.05	9554	2389	11%	150	50
260	0.05	10350	2588	12%	160	50
280	0.05	11146	2787	14%	160	60

Table 4.14 SS 1.4923, Tool 4 Varying Speed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.
- The max available speed on the machine on 12000 rpm, hence testing concludes here.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
150	0.07	5971	2090	7%	160	60
150	0.09	5971	2687	8%	210	70
150	0.11	5971	3284	9%	230	70

Table 4.15 SS 1.4923, Tool41 Varying Feed

- Smooth cutting, acceptable cutting sound and good surface finish observed for the feed of 0.07. whereas a few feed marks are observed on the surface for feeds of 0.09 and 0.11mm.

TOOL 5

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
150	0.05	5971	1493	7%	280	110
120	0.05	4777	1194	5%	320	110

Table 4.16 SS 1.4923, Tool 5 Varying Speed

- Abnormal cutting sounds are observed in all cases. Surface finish patterns are quite uneven, and the value of straightness fluctuates rapidly along the line of measurement.
- As moved horizontally along the second line of measurement even a negative value was observed, which is the first during this entire course of testing.
- Surface finish worsens at 120 m/min, hence 150 m/min is the ideal start point.
- Also feed marks are observed after the spring pass, showing us how not suitable the tool is.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
150	0.03	5971	896	5%	160	50
170	0.03	6768	1015	5%	-	-

Table 4.17 SS 1.4923, Tool 5 Varying Feed

- Since we have observed unacceptable outcomes, feed has been reduced and kept constant.
- In the first feed of 0.03mm abnormal cutting sounds are observed along with vibrations and feed marks on the machined surface.
- In the second case the straightness/tool bending cannot be measured due to the unevenness in the surface.

END OF SS 1.4923

4.1.3. Material 3, (Stainless Steel) SS 316L, (M-Class)

- For all testing values of A_p (40mm), A_e (0.4mm), no of passes (4) and stock of 1.6mm will remain constant.
- Coolant was used for the material.
- A feed of 0.05 mm/rev will not be breached for this material considering its hardness and machinability, instead machining will be carried with varying cutting speeds for a feed value of 0.05 mm/rev and 0.03 mm/rev.

TOOL 1

- Testing for tool 1 for varying cutting speeds.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.05	3583	716	4%	165	40
70	0.05	2787	557	2%	150	40
110	0.05	4379	876	4%	160	60
130	0.05	5175	1035	7%	160	60
150	0.05	5971	1194	7-8%	170	60

Table 4.18 SS 316L, Tool 1 Varying Speed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
70	0.03	2787	334	1%	110	20
90	0.03	3583	430	2%	115	20
110	0.03	4379	525	5%	120	30
130	0.03	5175	621	4%	125	40
150	0.03	5971	717	5%	130	40
170	0.03	6768	812	7%	130	50
200	0.03	7962	955	7%	140	50
220	0.03	8758	1051	8%	140	50
240	0.03	9554	1146	9%	130	50
280	0.03	11146	1338	12%	140	55

Table 4.19 SS 316L, Tool 1 Varying Feed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.

TOOL 2

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.05	3583	716	4%	190	80
110	0.05	4379	876	6%	220	90
130	0.05	5175	1035	8%	250	120

150	0.05	5971	1194	8-%	230	125
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Table 4.20 SS 316L, Tool 2 Varying Speed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
70	0.03	2787	334	2%	200	90
90	0.03	3583	430	4%	210	100

Table 4.21 SS 316L, Tool 2 Varying Feed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.

TOOL 4

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.05	3582	896	4%	200	80
110	0.05	4378	1094	5%	210	80
130	0.05	5175	1294	7%	220	85
150	0.05	5971	1493	8%	240	90
70	0.03	2787	418	2%	180	60
90	0.03	3283	538	2%	190	70

Table 4.22 SS 316L, Tool 4 Varying Speed/Feed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.

TOOL 5

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.05	3582	896	4%	380	200
90	0.03	3582	538	4%	310	120

Table 4.23 SS 316L, Tool 5 Varying Speed/Feed

- Abnormal cutting sound and bad/unacceptable surface finish observed in both cases.

4.1.4. Material 4, Titanium Alloy, TiAl₆V₄ (S-Class)

- For all testing values of Ap (40mm), Ae (0.4mm), no of passes (4) and stock of 1.6mm will remain constant.
- Coolant was used for the material.

TOOL 1

Vc (m/min)	f (mm/r ev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.05	3582	716	2%	75	20
110	0.05	4378	876	2%	80	25
130	0.05	5175	1035	4%	100	30
150	0.05	5971	1194	4%	100	40
170	0.05	6768	1354	4%	110	45
200	0.05	7961	1592	7%	110	40

Table 4.24 TiAl₆V₄, Tool 1 Varying Speed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.07	3582	1003	2%	90	30
90	0.09	3582	1290	2%	100	40
90	0.11	3582	1576	4%	120	50
90	0.13	3582	1863	4%	130	55

Table 4.25 TiAl₆V₄, Tool 1 Varying Feed

- Smooth cutting, acceptable cutting sound and good surface finish observed in the first two cases. In the last two some feed marks are observed.

TOOL 2

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.05	3582	716	4%	220	90
110	0.05	4378	876	5%	230	110

Table 4.26 TiAl₆V₄, Tool 2 Varying Speed

- Smooth Cutting, acceptable cutting sound and good surface finish is observed. However, wear on the cutting edges is observed. Hence, machining concludes here.

TOOL 4

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.05	3582	896	2%	120	45
110	0.05	4378	1095	3%	120	45
130	0.05	5175	1294	4%	110	50
150	0.05	5971	1493	5%	110	50
170	0.05	6768	1692	5%	110	50
200	0.05	7961	1191	7%	110	50

Table 4.27 $TiAl_6V_4$, Tool 4 Varying Speed

- Smooth cutting, acceptable cutting sound and good surface finish observed for all the above cases.

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.07	3582	1254	2%	115	50
90	0.09	3582	1612	2%	120	50
90	0.11	3582	1970	4%	140	50
90	0.13	3582	2328	4%	140	60

Table 4.28 $TiAl_6V_4$, Tool 4 Varying Feed

- Smooth cutting, acceptable cutting sound and observed for all the above cases. Some disturbances in the surface finish is also observed.

TOOL 5

Vc (m/min)	f (mm/rev)	N (RPM)	Vf (mm/min)	Spindle load	Tool bending (microns)	Spring Pass (microns)
90	0.05	3582	896	2%	190	90
110	0.09	4378	1095	4%	200	100
90	0.07	3582	1259	2%	210	115

Table 4.29 $TiAl_6V_4$, Tool 5 Varying Speed/Feed

- Smooth cutting, acceptable cutting sound and good surface finish observed in the first two cases. Some disturbances in the surface finish are seen in the last case.

4.2 Comparative Analysis

4.2.1 Results for Varying Feed

Below are the graphs plotted to analyse the effects of incremental feed on tool bending while keeping the cutting speed constant. Each graph contains the data measured for all the tools used for one material, hence four graphs are plotted for four different materials used, and the behaviour of the tools with respect to cutting feed is analysed.

- Material 1 CK45

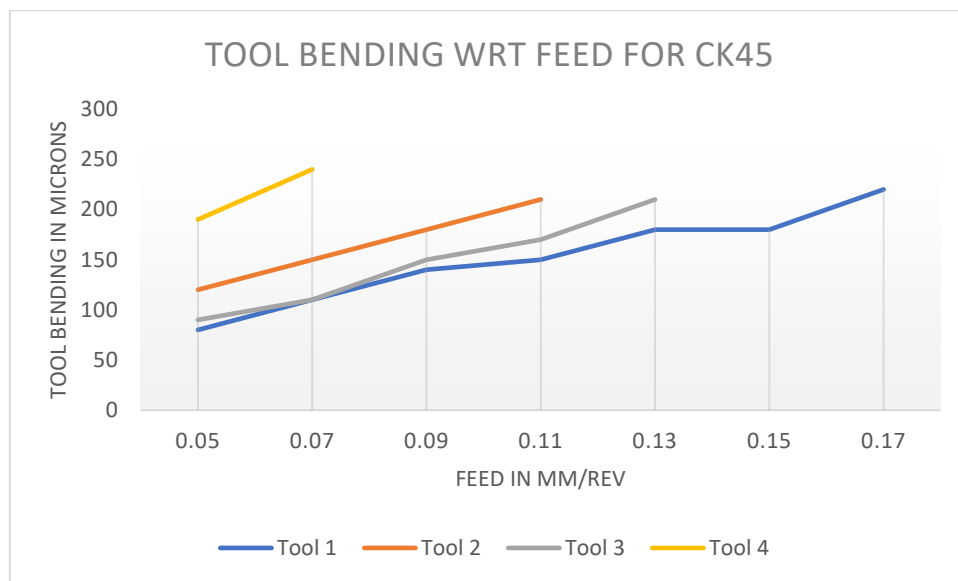


Fig 4.1 Tool Bending wrt varying Feed for CK45

- Material 2 SS 1.4923

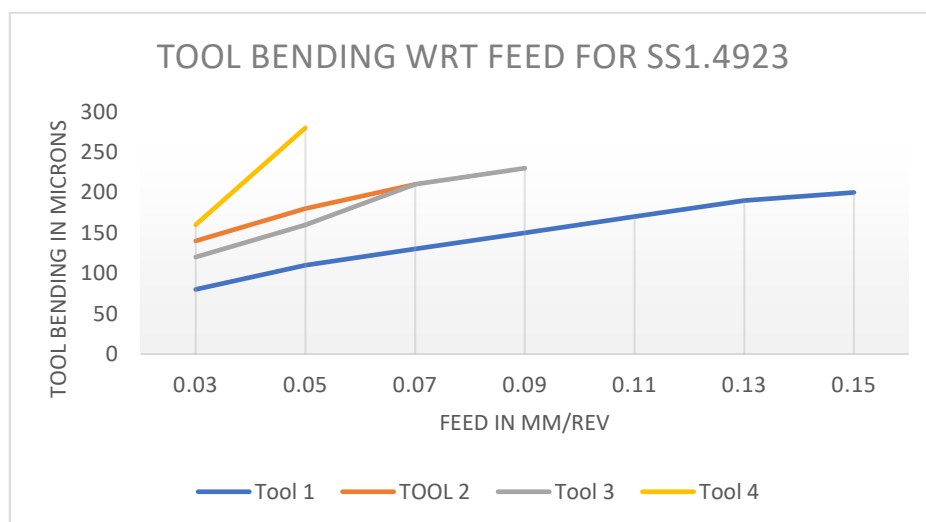


Fig 4.2 Tool Bending wrt varying Feed for SS 1.4923

- Material 3 SS 316L

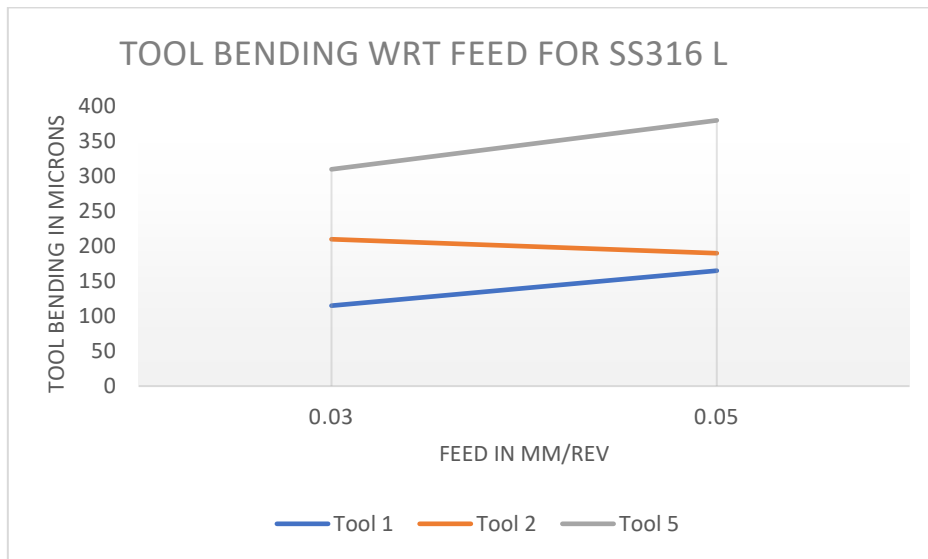


Fig 4.3 Tool Bending wrt varying Feed for SS 316L

- Material 4 TiAl₆V₄

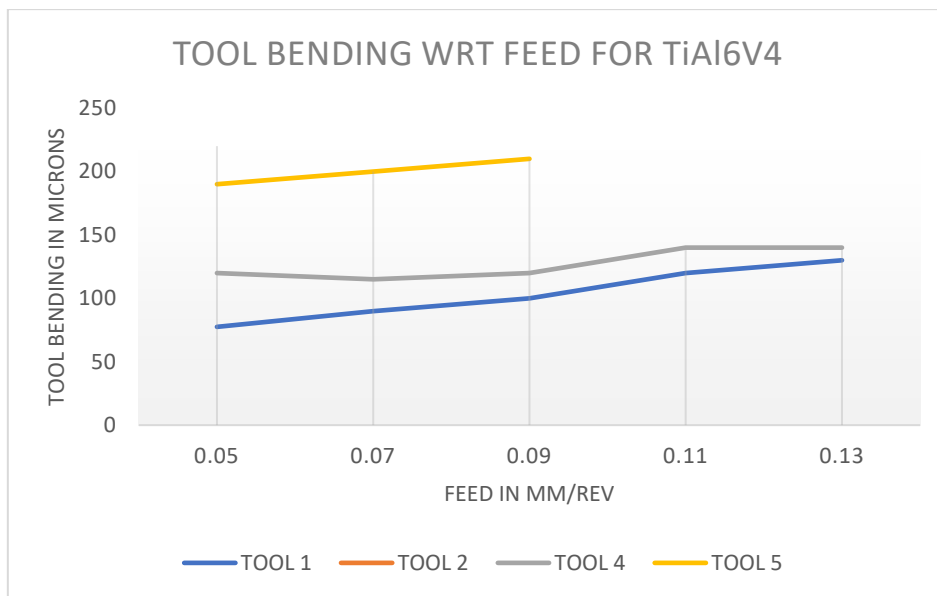


Fig 4.4 Tool Bending wrt varying Feed for TiAl₆V₄

4.2.2 Results for Varying Speed

Below are the graphs plotted to analyse the effects of incremental cutting speed on tool bending while keeping the feed constant. Each graph contains the data measured for all the tools used for one material, hence four graphs are plotted for four different materials used, and the behaviour of the tools with respect to cutting feed for a value of 0.05 mm/rev is analysed. However, in case of SS 316L the feed had to be reduced also to 0.03 mm/rev due to its tough machinability.

- Material 1 CK 45 Steel

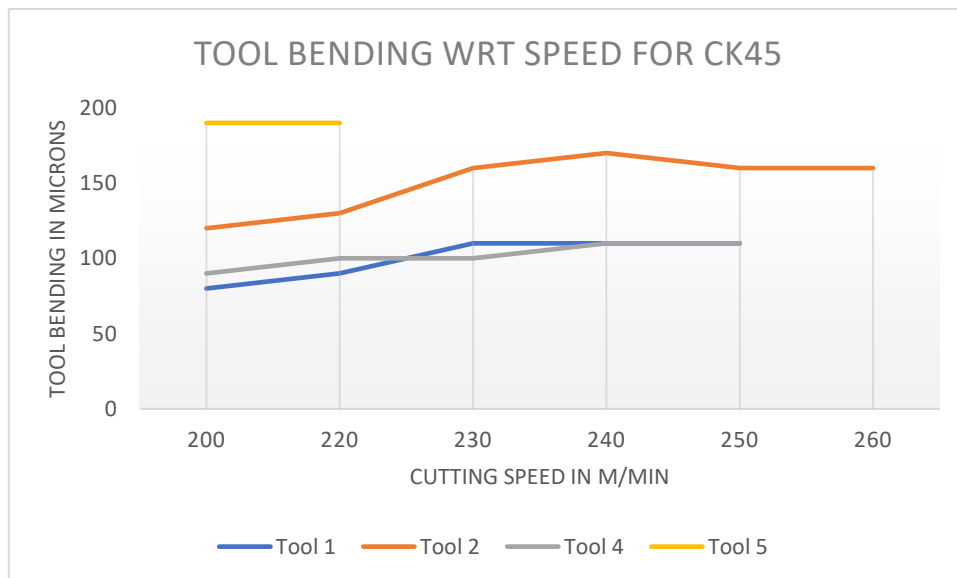


Fig 4.5 Tool Bending wrt varying Speed for CK 45

- Material 2 SS 1.4923

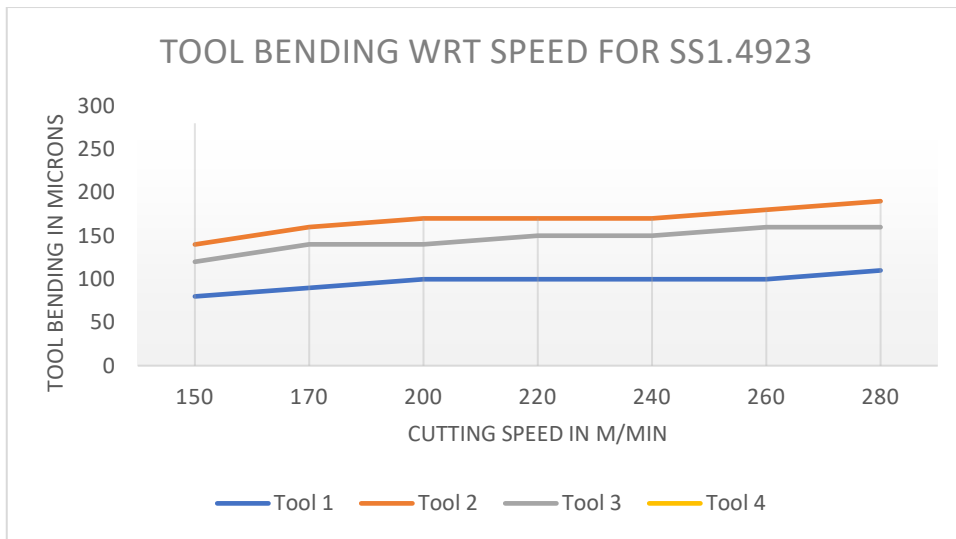


Fig 4.6 Tool Bending wrt varying Speed for SS 1.4923

- Material 3 SS 316L for a feed rate of 0.05 mm/rev

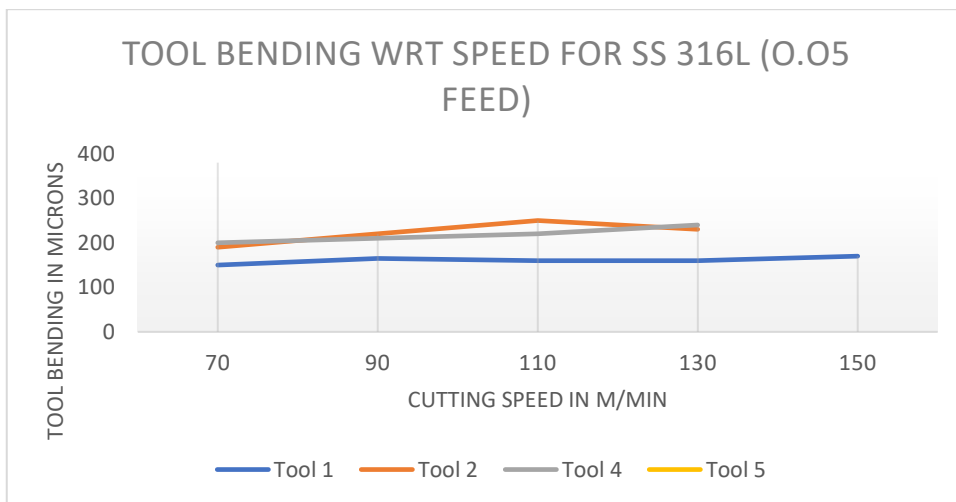


Fig 4.7 Tool Bending wrt varying Speed for SS 316L (feed is 0.05)

- Material 3 SS 316L for a feed rate of 0.03mm/rev

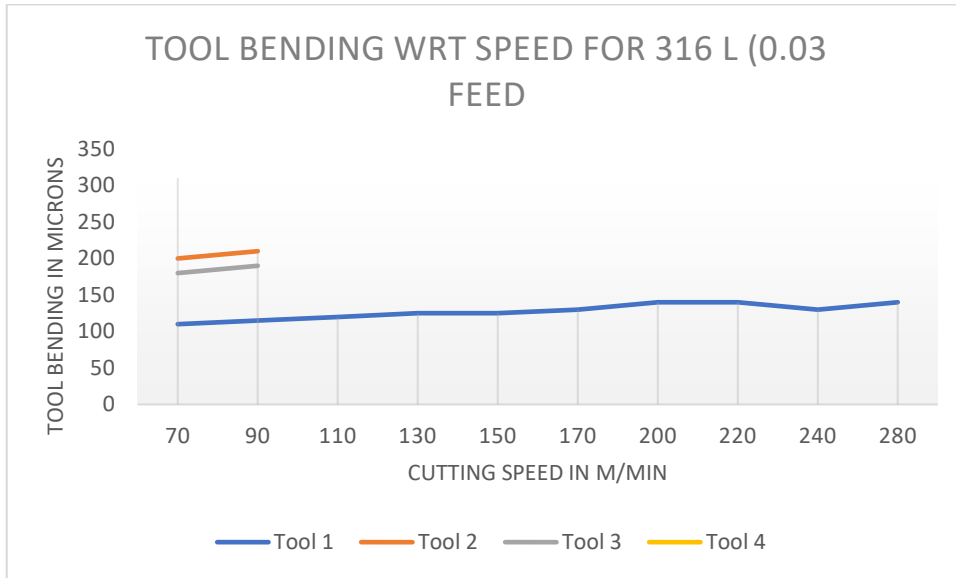


Fig 4.8 Tool Bending wrt varying Speed for SS 316L (feed is 0.03)

- Material 4 TiAl₆V₄

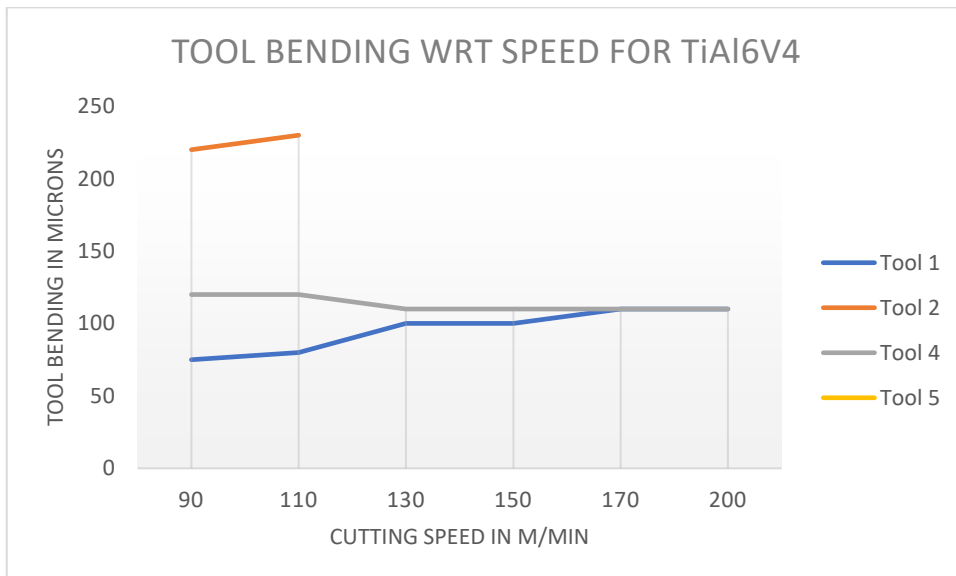


Fig 4.9 Tool Bending wrt varying Speed for TiAl₆V₄

Material 1

The cutting speeds employed for machining CK45 steel in this study ranged from 150 m/min to 280 m/min. The measured tool deflection values for tools 1, 2 and 4 were observed between 80 and 160 μm , whereas the tool 5 exhibited deflection values reaching up to 200 μm . This indicates superior performance of tools 1, 2 and 4 in terms of reduced tool bending. However, the increase in tool deflection with higher cutting speeds was gradual rather than abrupt. The experimental investigation was limited to this speed range due to machine spindle speed constraints, suggesting that the influence of cutting speed on tool bending was not significant under the given conditions. In all instances the resulting surface finish and process sound were found to be acceptable with an acceptable range of measured spindle load. Hence for a feed of 0.05mm/rev speed between 150m/min and 280 m/min can be used for this tool.

The feed rates applied to this tool range from 0.03 mm/rev to 0.17 mm/rev. Experimental measurements indicate that tool bending varies between 110 microns and 240 microns while maintaining load within acceptable limits on the spindle. Specifically, tool bending observed with Tools 1, 2 and 4 falls between 110 and 210 microns, whereas tool 5 exhibits a maximum deflection of 240 microns under identical conditions. The corresponding graph displays a consistent increase in tool bending with higher feed rates, suggesting that feed rate has a more pronounced effect on tool deflection compared to cutting speed. For instance, with Tool 1, surface quality degradation such as visible feed marks becomes evident at feed rates exceeding 0.15 mm/rev. Tool 2 shows an almost exponential rise in bending values as feed increases, while Tool 4 develops similar surface finish disturbances from a feed of 0.11 mm/rev onward. Furthermore, Tool 5 demonstrates unacceptable surface quality when the feed reaches 0.07 mm/min. Altogether, these findings reinforce that, relative to cutting speed, feed rate has a greater influence on both tool bending and the resulting workpiece surface integrity.

For Tool 3, premature tool failure occurred, the tool fractured during the second pass under the initial cutting parameters, thereby excluding it from the remainder of the experimental study.

Material 2

The cutting speed employed during testing for this material ranged from 150 m/min to 280 m/min. The measured tool deflection for the tools 1, 2 and 4 varied between 80 μm and 190 μm , whereas for the tool 5, deflection values reached as high as 320 μm . In the case of tools 1,2 and 4, testing indicated an acceptable surface finish with no noticeable variations in cutting sound. The trials were concluded not due to any limitation in tool performance, but rather because the spindle speed would have had to exceed 12,000 rpm to continue at higher cutting speeds. Conversely, for the tool 5, tool deflection values of 320 μm and 280 μm were observed at comparatively lower cutting speeds of 120 m/min and 150 m/min, respectively. These results were accompanied by a poor surface finish and irregular cutting sound, thereby demonstrating the superior performance of the tools 1, 2 and 4 in this aspect. Based on these findings, the recommended range of cutting speeds is 150–280 m/min with a feed rate of 0.05 mm/rev and with the other cutting parameters as specified in the experimental procedure. Additionally, there remains potential to extend the cutting speed to higher values.

The feed rate during testing was varied between 0.05 mm/rev and 0.17 mm/rev. For the tools 1,2 and 4, the measured tool deflection ranged from 80 μm to 230 μm . Unlike the cutting speed trials, which were limited by the machine's maximum spindle speed, the feed rate trials were concluded whenever either disturbances in surface finish were observed or the predefined upper limit of tool deflection was exceeded. For Tool 1, surface finish deterioration was first observed at a feed rate of 0.13 mm/rev, and the effect worsened with further increases. For Tool 2, the upper limit of tool deflection was breached at 0.09 mm/rev. Similarly, for Tool 4, surface finish deterioration was detected at 0.09 mm/rev. These observations reinforce that feed rate has a greater influence on tool deflection compared to cutting speed. In contrast tool 5 exhibited significantly higher tool deflection, along with unacceptable surface finish and cutting noise, even at the minimum feed rate of 0.05 mm/rev.

Material 3

For SS 316L, the experimental procedure differed slightly from that of the other materials. This variation was necessary as SS 316L, owing to its relatively higher hardness, presents greater challenges in machining. Consequently, the feed rate was restricted to 0.05 mm/rev and 0.03 mm/rev. At these feed values, the tool deflection was observed to exceed the initially defined limit of 200 μm once again showing its impact of tool bending to be larger than the impact of cutting speed, however testing was continued since such behaviour was anticipated given the difficulty of machining this material. The higher hardness of SS 316L also led to elevated temperatures during cutting, necessitating the use of coolant. Additionally, both the minimum and maximum cutting speeds were reduced significantly to accommodate the material's machinability constraints.

For a constant feed rate of 0.05 mm/rev, the cutting speed was limited to a range of 90 m/min to 150 m/min. The measured tool deflection for the tools 1,2 and 4 tools lay between 160 μm and 230 μm , which is notably higher compared to the values obtained for other materials. In all cases, the experiments were terminated once the deflection exceeded the acceptable limits, as proceeding further posed a risk of tool damage. Despite the relatively high tool bending, the surface finish and cutting sound remained acceptable, and spindle load was observed to be minimal. In contrast, the tool 5 exhibited poor performance, with both surface finish and cutting sound found to be unacceptable, again highlighting the superior performance of the tools 1,2 and 4 in this comparative evaluation.

For a constant feed rate of 0.03 mm/rev, the cutting speed was varied between 70 m/min and 280 m/min. The measured tool deflection for the tools 1, 2 and 4 ranged from 110 μm to 210 μm . In all cases, the resulting surface finish was smooth and free from disturbances, with normal cutting sound observed throughout. In contrast, the tool 5 produced unacceptable surface finishes with noticeable disturbances, and the cutting sound was abnormal even at the lowest cutting speed values.

Material 4

Similar to stainless steel grade 316L, TiAl₆V₄ also exhibits relatively high hardness and reduced machinability compared to the first two materials. Consequently, the range of cutting speeds employed for this material was significantly lower. However, since TiAl₆V₄ is not as difficult to machine as SS 316L, experiments were also conducted with varying feed rates. Coolant was used during these trials, as the cutting temperatures generated were sufficiently high to accelerate tool wear.

For a constant feed rate of 0.05 mm/rev, cutting speeds ranged from 90 m/min to 200 m/min. Tool deflection for tools 1, 2 and 4 measured between 75 µm and 230 µm across this range. Tool 5 exhibited a tool deflection of 190 µm at the initial cutting parameter set, resulting in the cessation of further testing. Tools 1, 2 and 4 consistently produced smooth surface finishes and stable cutting sounds throughout the tested parameters.

The feed rate in this experiment was varied between 0.05 mm/rev and 0.13 mm/rev. The measured tool deflection ranged from 90 µm to 210 µm. Testing was discontinued in each case due to observed variations in surface finish and cutting sound. For Tool 1, deviations from the desired results were noted at a feed rate of 0.11 mm/rev. Tool 2 exhibited undesirable results throughout the tested feed range. Tool 4 maintained acceptable results across all feed values, whereas Tool 5 demonstrated unacceptable outcomes starting from the initial increase in feed rate.

5. Conclusions

- Objective 1: Investigate the influence of varying cutting speed and feed rate on tool bending in solid carbide end mills (hypothesizing stronger feed rate influence).

Experiments across CK45, SS 1.4923, SS 316L, and Ti-6Al-4V confirmed feed rate exerts a stronger effect than cutting speed, with deflections often exceeding 200 μm at higher feeds (e.g., 0.11-0.17 mm/rev) while speed variations up to machine limits (280 m/min) rarely caused comparable issues or surface degradation.

- Objective 2: Create and test a practical setup for accurately measuring tool bending during real machining tests.

The dial gauge-based surface straightness method (three positions, <10 μm variation tolerance, spring pass validation) proved reliable, yielding consistent measurements below 100-250 μm thresholds where feasible, supplemented by visual/auditory checks for surface finish and sound when initial limits proved challenging.

- Objective 3: Perform comparative analysis of solid carbide end mills of different designs under identical conditions (evaluating bending, surface quality, process window).
- Tools 1, 2, and 4 outperformed Tools 3 (fractured early) and 5 (High deflections >300 μm , poor finish), showing lower bending (80-190 μm typical), stable operation, and wider usable windows (e.g., 150-280 m/min at 0.05 mm/rev for Ti-6Al-4V).

From the analysis of the experimental results, it can be concluded that the effect of feed rate on tool bending is significantly more pronounced than that of cutting speed. Although the range of cutting speeds employed in the experiments was substantially higher than the range of feed rates, tool deflection rarely exceeded 200 μm at elevated cutting speeds. In several instances, the limitation for cutting speed was imposed by the machine's maximum spindle speed capacity rather than by excessive tool bending or compromised machining quality. Conversely, variations in feed rate consistently resulted in diminished surface quality, compelling the cessation of machining operations due to unacceptable surface finish rather than machine constraints.

Furthermore, the comparative evaluation of the tested tools clearly demonstrates the superior performance of tools 1,2 and 4 relative to tools 3 and 5. These exhibited lower tool deflection values, more stable cutting sounds, and better surface finishes across the breadth of tested cutting parameters. This experimental study not only provides insight into the distinct influences of feed and cutting speed on tool deflection and machining quality but also offers an opportunity to benchmark these tools. Additionally, the results have facilitated the development of an optimized range of cutting parameters, contributing to enhanced tool utilization and machining efficiency for the tested tools.

6. Gallery

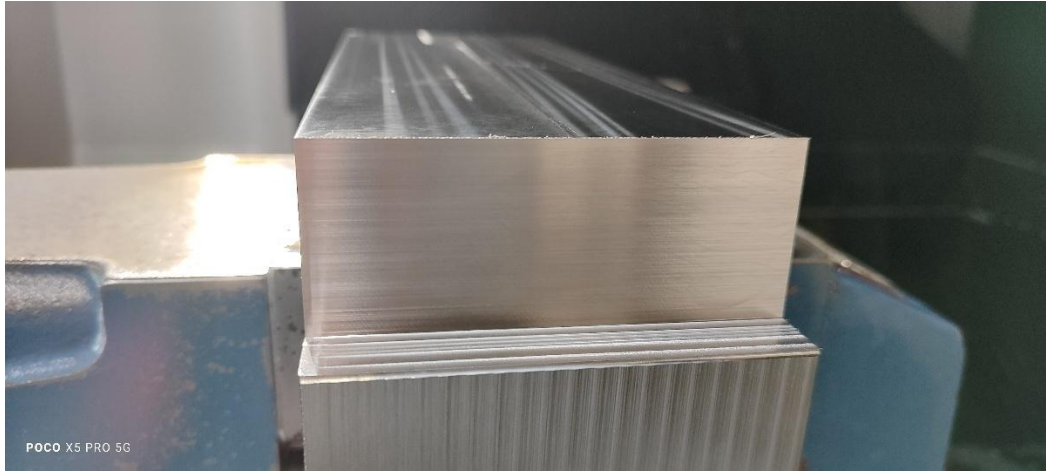


Fig 6.1 : *Example of good surface finish 1*

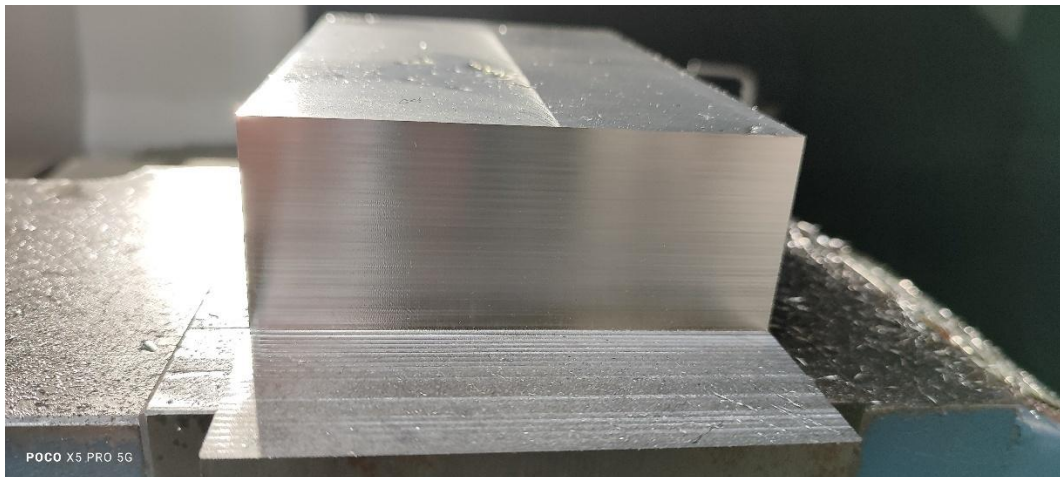


Fig 6.2 : *Example of good surface finish 2*

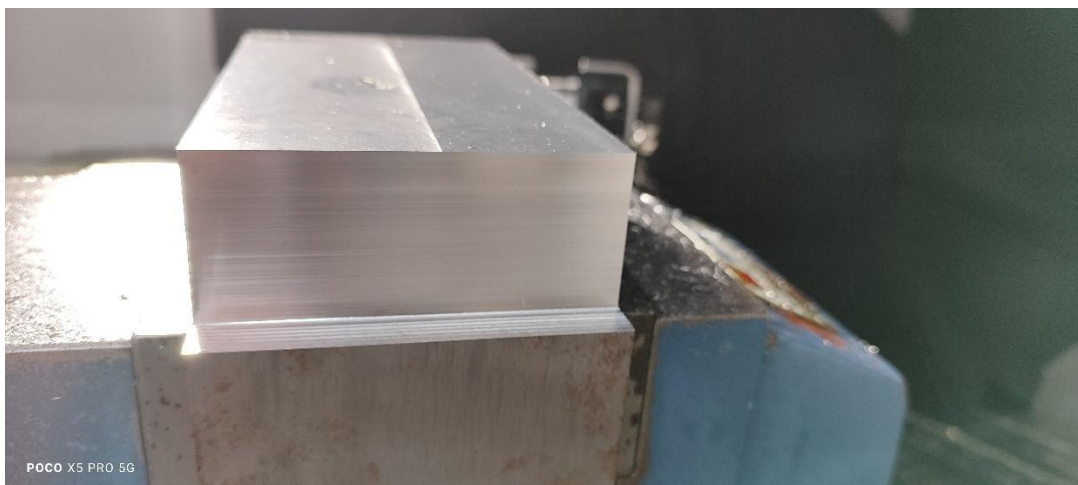


Fig 6.3 : *Example of good surface finish 3*

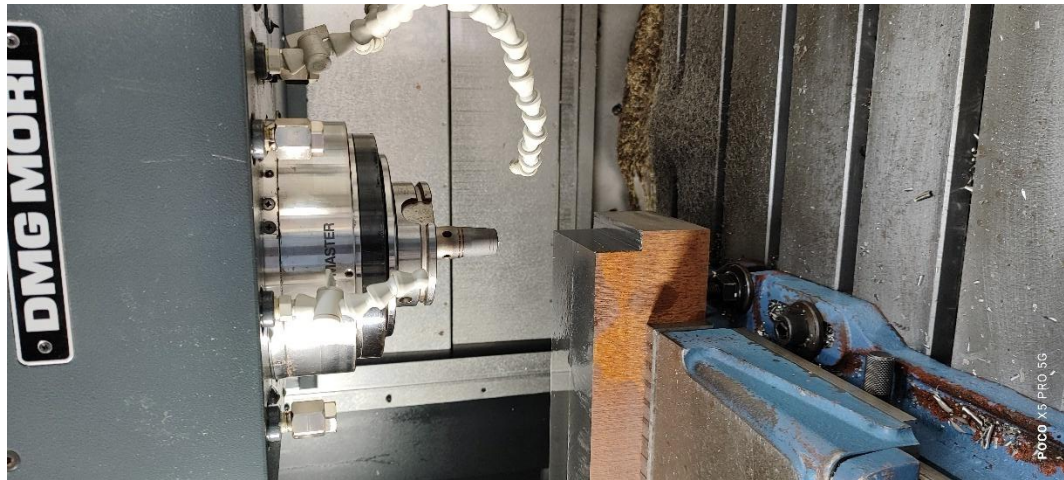


Fig 6.4 : *Experimental Setup*



Fig 6.5 : *Measurement of tool bending*

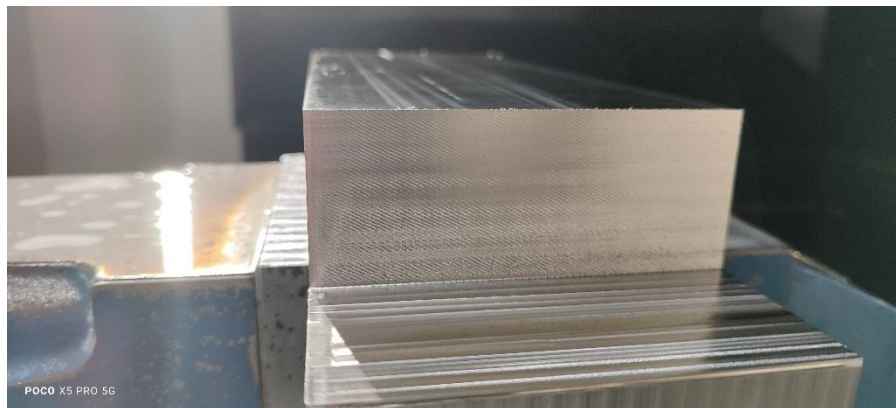


Fig 6.6 : *Example of unaccepted surface finish*

7. Individual Graphs

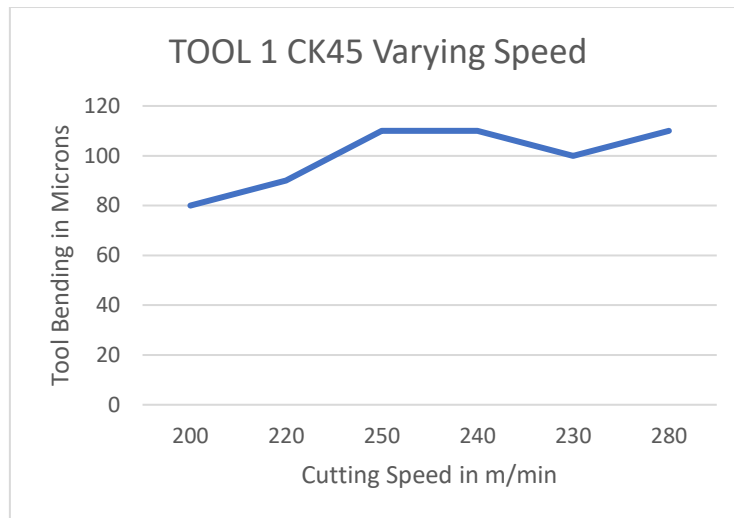


Fig 7.1 Tool Bending wrt varying speed for tool1 (CK45)

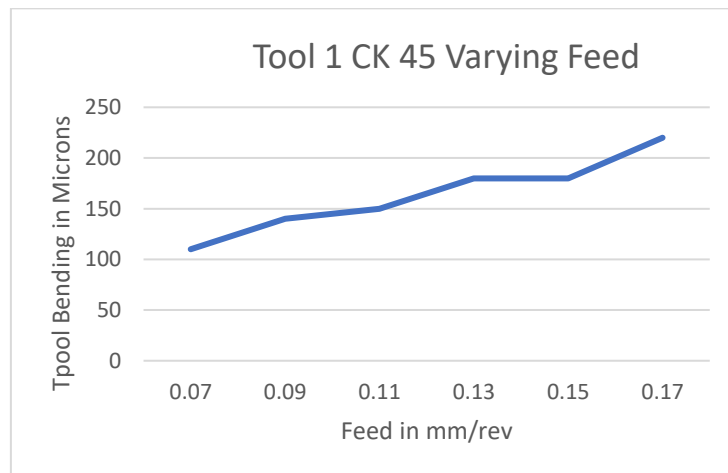


Fig 7.2 Tool Bending wrt varying feed for tool1 (CK45)

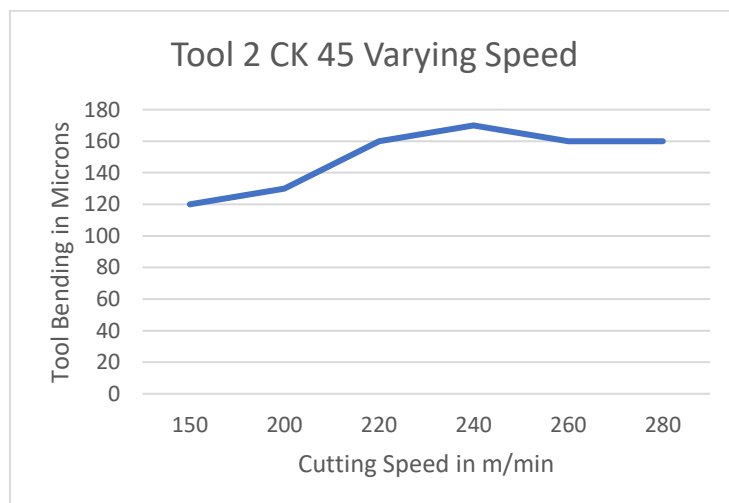


Fig 7.3 Tool Bending wrt varying speed for tool2 (CK45)

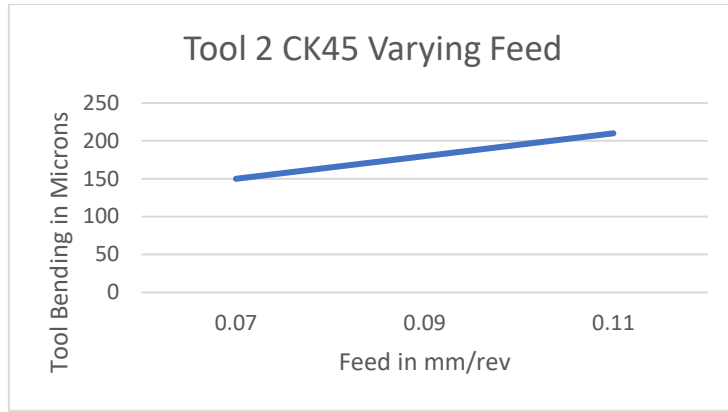


Fig 7.4 Tool Bending wrt varying feed for tool2 (CK45)

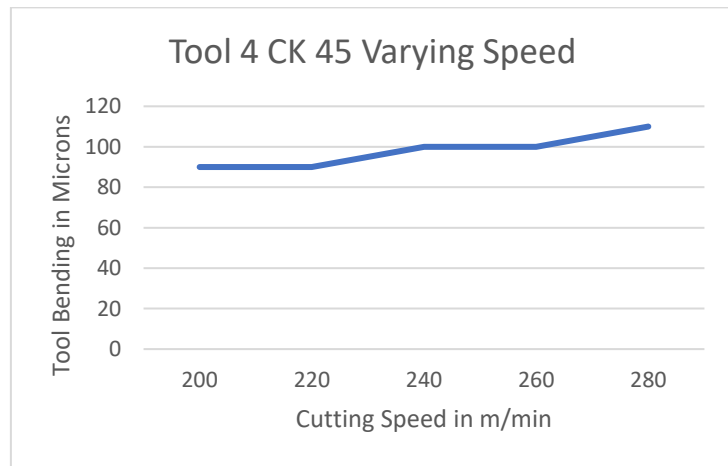


Fig 7.5 Tool Bending wrt varying speed for tool4 (CK45)

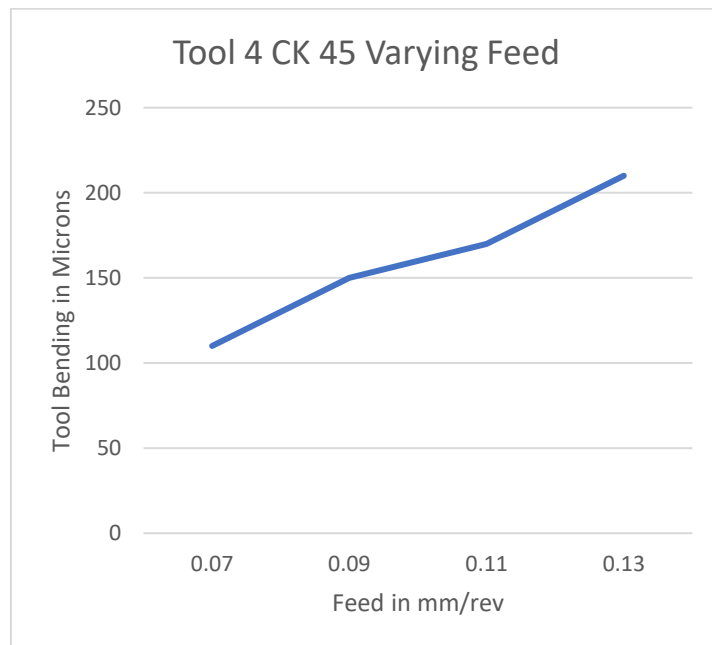


Fig 7.6 Tool Bending wrt varying feed for tool4 (CK45)

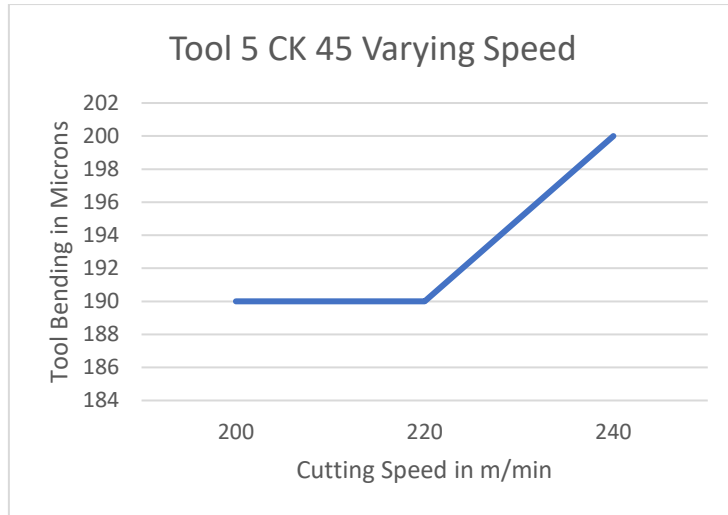


Fig 7.7 Tool Bending wrt varying speed for tool5 (CK45)

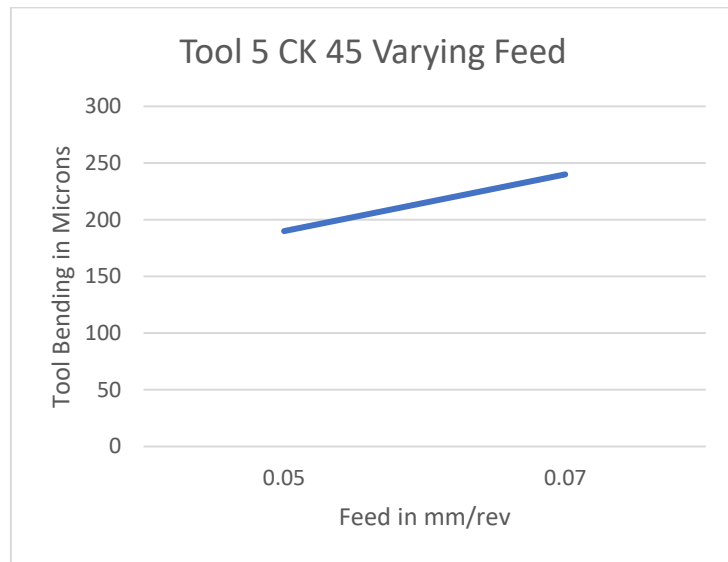


Fig 7.8 Tool Bending wrt varying feed for tool5 (CK45)

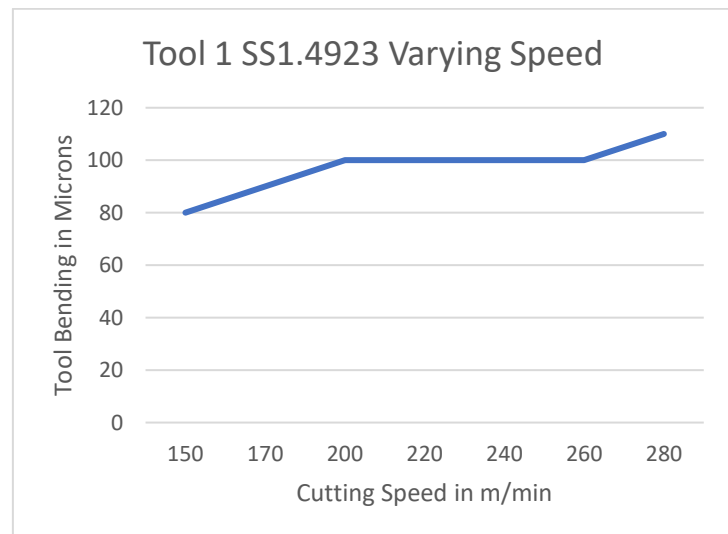


Fig 7.9 Tool Bending wrt varying speed for tool1 (SS 1.4923)

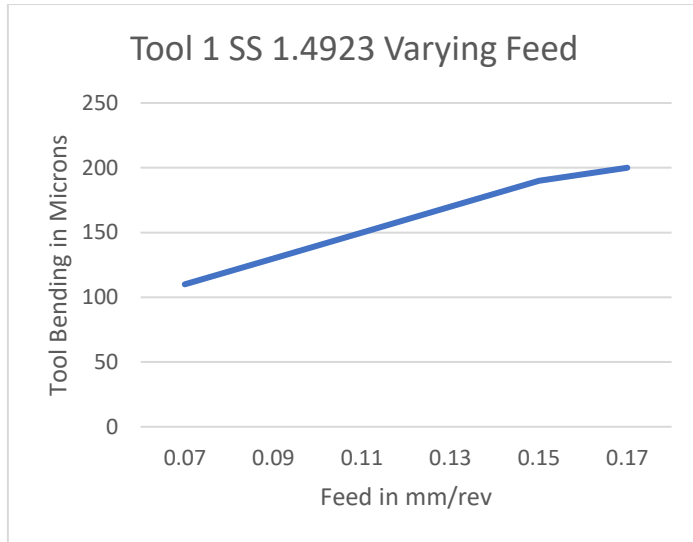


Fig 7.10 Tool Bending wrt varying feed for tool1 (SS 1.4923)

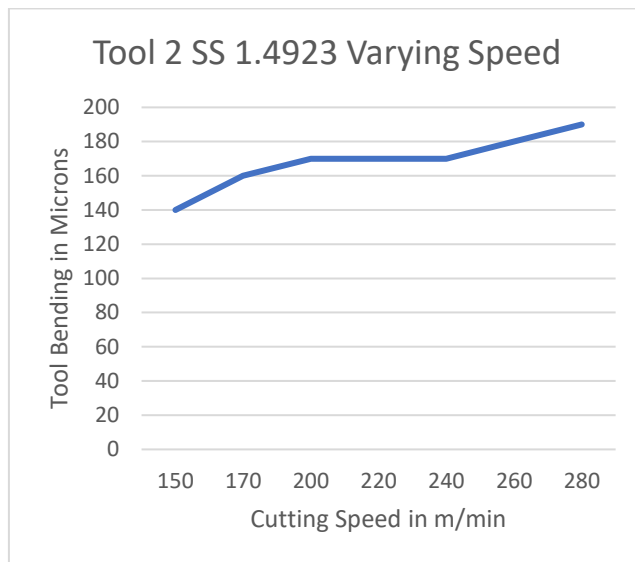


Fig 7.11 Tool Bending wrt varying speed for tool2 (SS 1.4923)

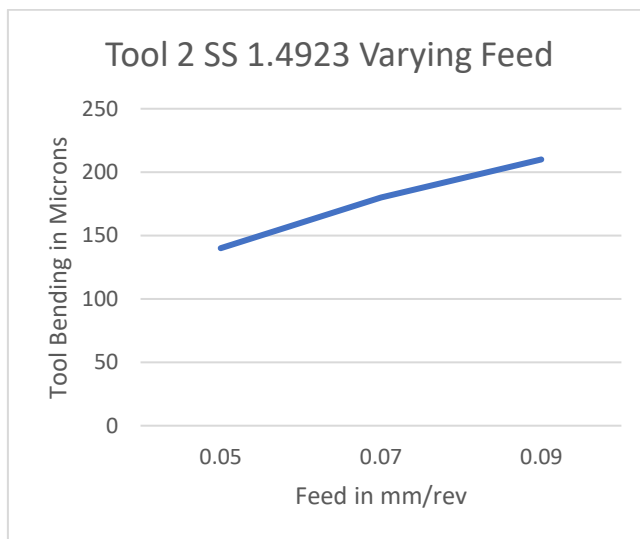


Fig 7.12 Tool Bending wrt varying feed for tool2 (SS 1.4923)

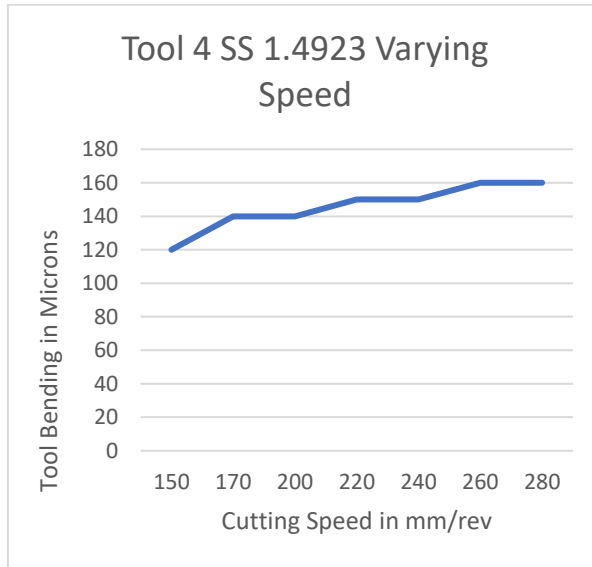


Fig 7.13 Tool Bending wrt varying speed for tool4 (SS 1.4923)

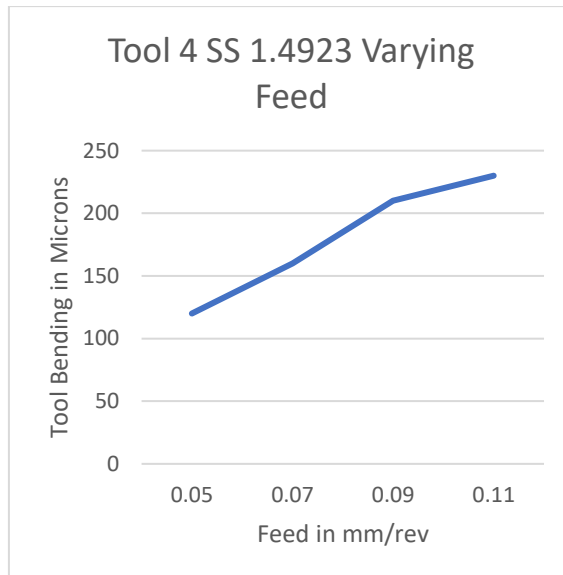


Fig 7.14 Tool Bending wrt varying feed for tool4 (SS 1.4923)

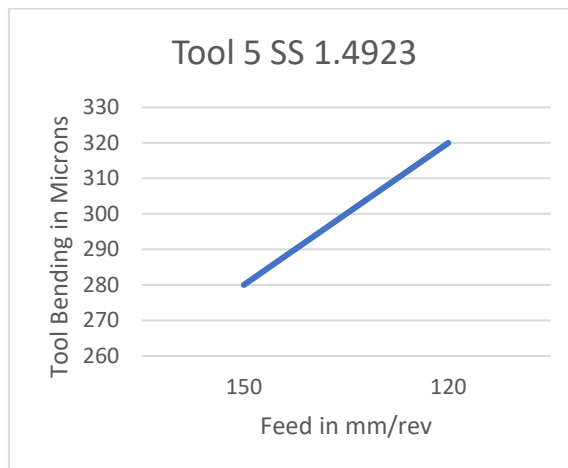


Fig 7.15 Tool Bending wrt speed and feed for tool5 (SS 1.4923)

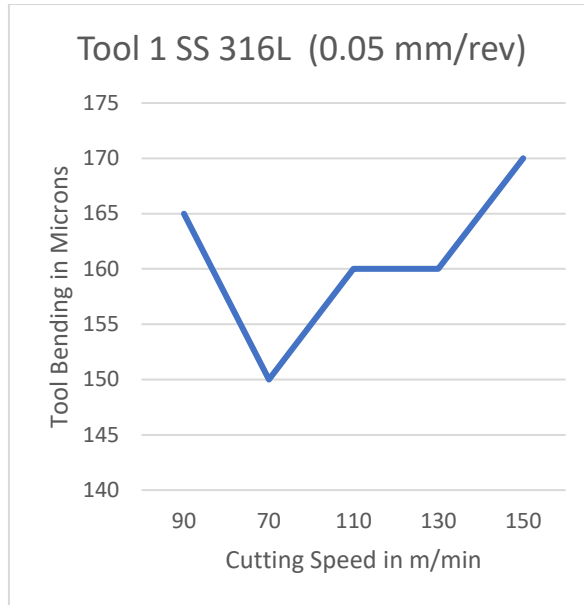


Fig 7.16 Tool Bending wrt varying speed at 0.05mm feed for tool1 (SS 316L)

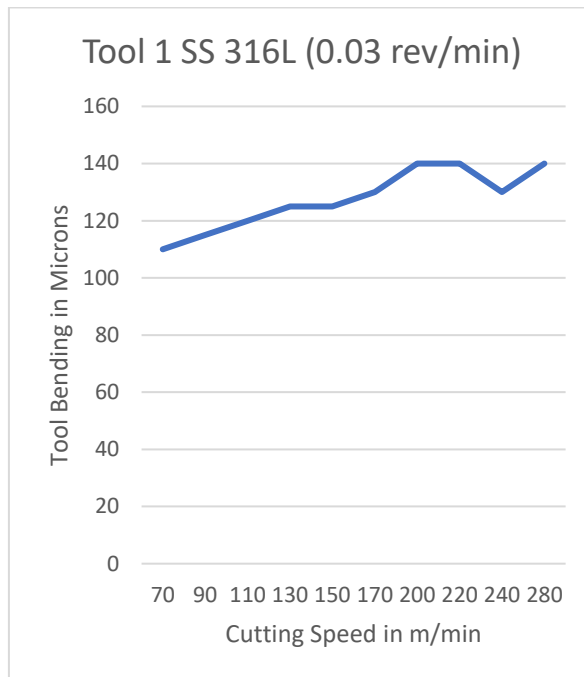


Fig 7.16 Tool Bending wrt varying speed at 0.03mm feed for tool1 (SS 316L)

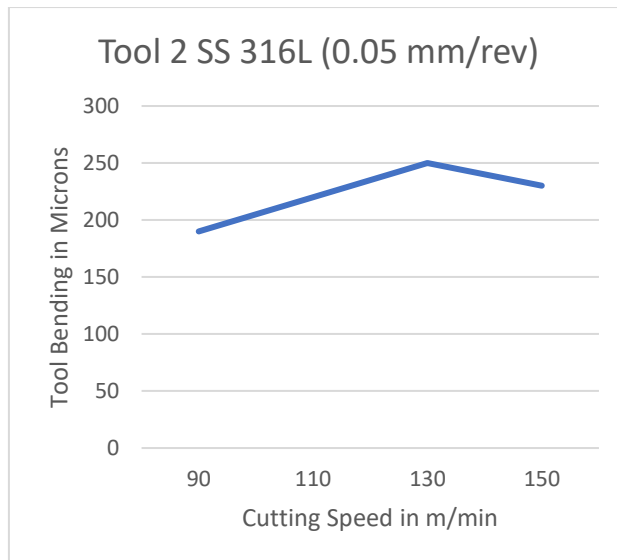


Fig 7.16 Tool Bending wrt varying speed at 0.05mm feed for tool2 (SS 316L)

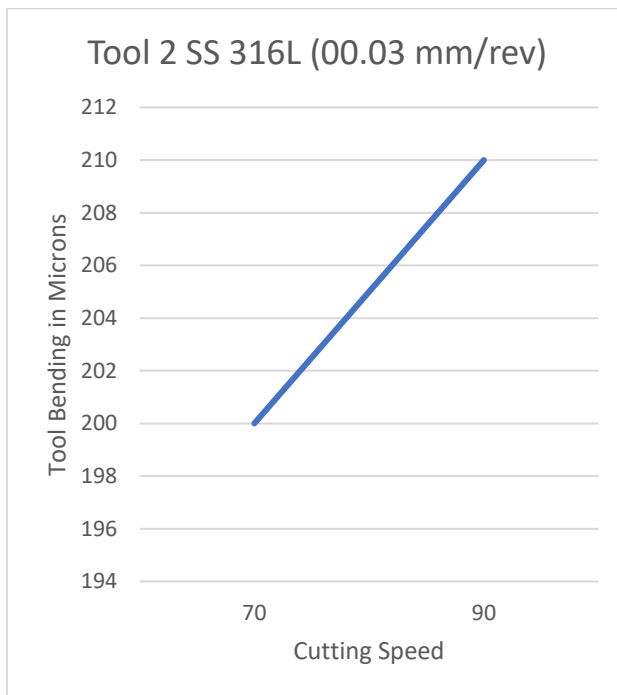


Fig 7.16 Tool Bending wrt varying speed at 0.03mm feed for tool2 (SS 316L)

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