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TOLERANCE COST IN RELATION TO SURFACE FINISH DURING LONGITUDINAL TURNING OPERATIONS

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Abstract: Tolerances are an important part of production where the desire to produce quality products have to be weighed against the increased production costs. The desired tolerance will influence the choice of both production method as well as the machine used. Given that machining is an adequate production method, variation of the required surface roughness will imply a variation of the part cost which needs to be taken into account during production planning. This paper presents a method for evaluating the tolerance cost in regards to surface roughness during longitudinal turning operations, thus enabling a better comparison between different production situations.

Keywords: Machining, Turning, Tolearnce cost, Surface roughness, Part cost.

1. INTRODUCTION

The quality of any given part is commonly defined through using one or more dimensional and surface roughness tolerances during production. The part is required to conform to these tolerances in order to be perceived as being of sufficient quality and thus not discarded. The tolerance levels are commonly set during the product development phase, principally illustrated in Fig. 12, where a certain level is determined in relation to what is required of the part in order to function properly in the designated product as well as to appeal to the customer and thus fulfilling the customer demands. It is however also important to note that the required tolerance level strongly influences the production process, and as a result the production cost, as for instance emphasized by Hsieh (2006). Typically the production cost could be expected to increase substantially as a function of decreasing a tolerance as for instance illustrated by Yeo, *et al.* (1996). It is also important to understand that the process sequence will have a significant influence on both the attained tolerance and production cost as stated by Yeo, *et al.* (1998) among others. Diplaris and Sfantsikopoulos (2000) have previously published a model for calculating the production cost as a function of the required tolerance. A problem with their model is however that it does not include the required surface roughness. In addition to the macro scale geometrical tolerances the surface roughness is a commonly used parameter while evaluating the quality of a finished part. Several different surface roughness parameters are today in common use in industry, one of the more common being the arithmetic mean surface roughness R_a. For many machined surfaces a maximum value of the surface roughness is defined during the product development phase as a result of aesthetic and functional incentives during the development process. It is however important to realize that while determining these values the production cost is also partially determined as a consequence. Depending on the required value of the surface roughness different or additional manufacturing process may be required. Even limited variations of the required surface roughness may have a significant influence on the cycle time, and thus the production cost, of a specific part.

2. ANALYTICAL DETERMINATION OF R_a

The authors have previously published an analytical equation, Equation 1, for calculation of the R_a surface roughness during longitudinal turning operations (Ståhl, *et al.*, 2012). In Equation 1 f is the feed and r is the tool nose radius during the specific turning operation. Equation 1 is only valid if a radius-radius contact exists between the nose radius of the cutting tool for two consecutive revolutions of the workpiece, Case A, as previously described by several authors (Puhasmägi, 1973; Ståhl, 2012a; Isaev, 1950), Fig. 1. Bus, *et al.* (1971) makes an attempt to solve same problem, unfortunately with some errors, which later were corrected by Hägglund (2013). It can be analytically proven that Case A in Fig. 1 implies a condition on the size of the feed f in relation to the tool nose radius r and minor cutting edge angle κ_b, Equation 2.

$$R_{a,theoretical} \approx 0.77 \cdot \left[r - \frac{r^2}{f}\sin^{-1}\left(\frac{f}{2r}\right) - \frac{r}{2}\sqrt{1-\frac{f^2}{4r^2}} \right] \quad (1)$$

$$f \le 2 \cdot r \cdot \sin\kappa_b \quad (2)$$

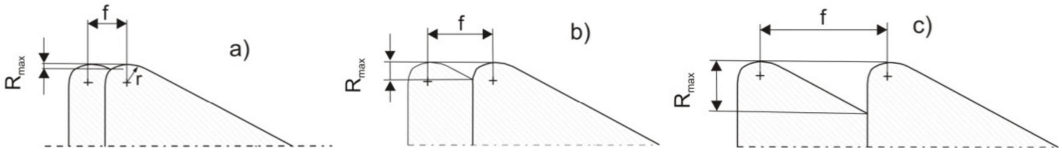

Fig. 1. Principle illustration of three different combinations of feed and nose radius (Puhasmägi, 1973).

Later research has also shown how ploughing of the machined surface may significantly alter the surface roughness from the theoretically expected value, Fig. 2. However, through adding an additional part to the theoretical equation a more accurate model could be obtained as validated through previous research (Schultheiss, *et al.*, 2014), Equation 3.

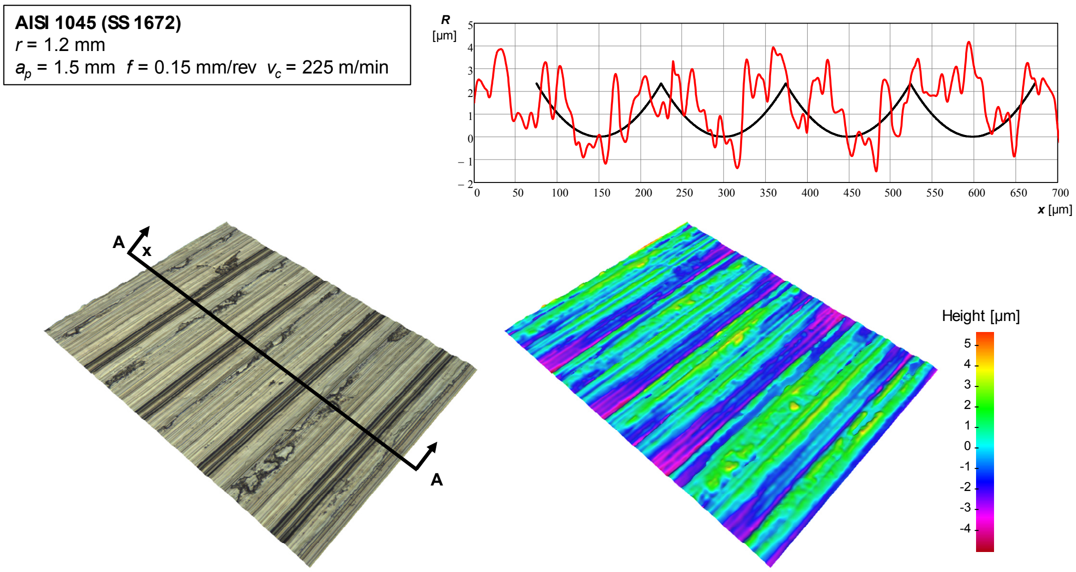

Fig. 2. Obtained surface micro topography while longitudinally turning AISI 1045, (Schultheiss, 2013). The 2D-graph illustrates the measured (black) and theoretical surface roughness, Equation 2 (red).

In Equation 3 R_{h1min}, as defined in Equation 4, is a function of the ploughing area A_{pl}, defined in Equation 5, intended to describe the amount of material plastically deformed on the workpiece surface during the machining operation. In Equation 3 both R_0 and χ are model constants which need to be determined empirically for each machining situation. The χ constant could be interpreted as the amount of plastically deformed material which is left on the machined surface and thus contributing to a variation of the surface roughness from the theoretically expected value. The R_0 constant is intended to correct the proposed model for factors influencing the attained surface roughness which are not yet included in the model, e.g. vibrations, unexpected tool wear, etc. Finally, ω is a variation factor used to describe the potential for the R_a value to fluctuate under seemingly equivalent machining conditions. During a general machining operation the ω value will attain two values, larger and smaller than 1, respectively. This will enable the user to define the range of potential surface roughnesses during a specific machining operation. As part of previous research, (Schultheiss, *et al.*, 2014), it was found that the variation factor ω generally attained almost equivalent values for all workpiece materials investigated. Thus, it was proposed that two universal values, 1.20 and 0.89, should be used for this constant independently of turning operation. It should however also be noted that an extra safety factor is advisable in order to attain machining conditions suitable for attaining the desired R_a surface roughness during a given machining scenario. In Equation 4 $h_1(\delta)$ is the theoretical chip thickness as h_1 as a function of the angular position δ defined according to Equation 6. In Equation 5 the angular positions δ_0 and δ_{h1min} are defined as the value of the δ angle at $h_1 = 0$ mm and $h_1 = h_{1min}$, respectively, Equation 7 and 8. h_{1min} in this case being the size of the minimum chip thickness.

$$R_a = \omega \cdot \left(R_{a,theoretical} + R_0 + \chi \cdot R_{h1\min}\right) \quad (3) \qquad R_{h1min} = \frac{A_{pl}}{f} \quad (4)$$

$$A_{pl} = \int_{\delta_0}^{\delta_{h1min}} h_1(\delta) \cdot \left(r - \frac{h_1(\delta)}{2}\right) d\delta \quad (5) \qquad h_1(\delta) = f \cdot \sin(\delta) + r - \sqrt{r^2 - f^2 \cos^2(\delta)} \quad (6)$$

$$\delta_0 = -\sin^{-1}\left(\frac{f}{2r}\right) \quad (7) \qquad \delta_{h1min} = -\sin^{-1}\left(\frac{f^2 - 2 \cdot r \cdot h_{1min} + h_{1min}{}^2}{2 \cdot f \cdot \left(r - h_{1min}\right)}\right) \quad (8)$$

Equations 5-8 have previously been defined by Ståhl (2012a). A previous investigation (Schultheiss, *et al.*, 2014) has revealed that the minimum chip thickness h_{1min} may be modeled as a function of the theoretical chip thickness h_1, Equation 9.

$$h_{1min} = h_{1min,0} \cdot \left[1 + \left(\frac{h_1}{h_{1,0}}\right)^{g_1}\right]^{\frac{g_2}{g_1}} \quad (9)$$

In this equation $h_{1min,0}$ is defined as h_{1min} at $h_1 < h_{1,0}$. In turn $h_{1,0}$ is defined as the breakpoint between the so called r_β-region and the v_{ch}-region in which the tool edge radius r_β and chip flow direction v_{ch}, respectively, has the primary influence on the size of h_{1min} (Schultheiss, *et al.*, 2011). g_1 and g_2 are both model constants which needs to be determined empirically. The definition of all variables used in Equation 1 to 9 can be found in Table 1.

Table 1. Definition of variables used for modeling the R_a surface roughness.

Var.	Description	Unit
A_{pl}	Ploughing area	mm²
f	Feed	mm/rev
g_1	Empirical model constant	-
g_2	Empirical model constant	-
h_1	Theoretical chip thickness	mm
$h_{1,0}$	Breakpoint between r_β- and v_{ch}-region	mm
h_{1min}	Minimum chip thickness	mm
$h_{1min,0}$	h_{1min} at $h_1 < h_{1,0}$	mm
r	Nose radius	mm
R_0	Addition to R_a due to unknown causes	µm
R_a	Arithmetic mean surface roughness	µm
$R_{a,theoretical}$	Theoretical R_a surface roughness	µm
R_{h1min}	Addition to R_a due to h_{1min} effects	µm
v_c	Cutting speed	m/min
δ	Angular position along the nose radius	°
δ_0	Angular position δ at $h_1 = 0$ mm	°
δ_{h1min}	Angular position δ at $h_1 = h_{1min}$	°
κ_b	Minor cutting edge angle	°
χ	Amount of A_{pl} left on the surface	-
ω	Variation factor	-

As obtained during a previous study, (Schultheiss, *et al.*, 2014), the following model constants were used while modeling the R_a surface roughness for each of the four investigated workpiece materials, i.e. A48-40B, AISI 4140, AISI 316L and Ti6Al4V, Table 2.

Equation 3 has previously been proven to be valid for use for predicting the attained R_a value for a range of different workpiece materials and machining conditions (Schultheiss, *et al.*, 2014). The same model may also be used for calculating the required feed needed in order to attain a certain R_a surface roughness given a predetermined tool nose radius and workpiece material. Thus, it is possible to use Equation 3 for calculating the required feed and thus in extension the engagement time necessary for attaining a specified R_a surface roughness.

Table 2. Model constants used for modeling the R_a surface roughness for each of the four materials.

Material	r [mm]	$h_{1min,0}$ [µm]	h_{10} [µm]	g_1	g_2	R_0 [µm]	χ [%]
	0.4	0.7	41	0.58	1.26	-1.18	1.68
A48-40B	0.8	9	51	0.57	1.21	-0.14	0.30
(SS 0125)	1.2	4	28	0.63	1.36	-3.05	2.82
	1.6	6	47	0.57	1.23	-0.94	0.99
	0.4	0.4	4	0.58	1.34	2.94	-6.10
AISI 4140	0.8	0.3	3	0.56	1.31	1.74	-2.91
(SS 2244)	1.2	4	46	0.54	1.21	-0.06	0.96
	1.6	1	18	0.56	1.27	-2.41	5.71
	0.4	2	23	0.54	1.27	-1.32	5.62
AISI 316L	0.8	5	59	0.52	1.17	-0.32	1.33
(SS 2348)	1.2	4	49	0.54	1.20	-0.31	-1.11
	1.6	4	61	0.54	1.81	-0.18	1.41
	0.4	3	29	0.55	1.27	-2.31	5.81
Ti6Al4V	0.8	1	11	0.60	1.35	2.42	-2.48
(-)	1.2	2	17	0.59	1.32	0.24	-0.04
	1.6	4	43	0.56	1.25	0.02	0.30

3. INFLUENCE OF WORKPIECE MATERIAL PROPERTIES

Previous research has shown that 5 material properties have a significant impact on the potential machinability of a specific workpiece material (Andersson and Ståhl, 2007; Xu, *et al.*, 2013). These 5 material properties were found to be the ductility, strain hardening, thermal conductivity, hardness and abrasiveness. These could each be considered as influencing the machinability of the workpiece material according to the following: Ductility: A high value of the ductility has been shown to regularly result in strong adhesion between the workpiece material and cutting tool. Also, the ductility of the workpiece material strongly relates to the form of the obtained chips where a low ductility commonly is considered as beneficial. Strain hardening: A high level of strain hardening generally implies that more energy is required for chip formation, resulting in higher cutting forces. In this implementation the strain hardening is defined as the ratio between the ultimate tensile strength R_m and the yield strength R_p of the workpiece material. Thermal conductivity: Heat is generally generated by plastic deformation and friction during metal cutting operations and a high rate of heat removal is needed in order to prevent a severe rise in temperature. Hardness: The hardness of the workpiece material strongly affects the deformation- and cutting resistance of the material during machining operations. Abrasiveness: Abrasive wear mechanisms commonly have a strong negative effect on the attained tool life during metal cutting operations. For instance Chou and Evans (1997) have found that hard particles, e.g. carbides, in the workpiece material can have a decisive influence on the attained tool wear. The relevant material properties as based on their relevance for the potential machinability can be found in Table 3 for each of the 4 evaluated workpiece materials. Through using the method previously described by for instance Xu, *et al.* (2013) it is possible to calculate the relative influence on the machinability for each of the 5 previously presented workpiece material properties with the exception of the abrasiveness. Due to the current lack of a reliable and generally applicable method for measuring the abrasiveness of a wide range of materials this factor has been excluded from the current comparison. As a result a relative value of 5 has been used for all materials during the current evaluation. This may however not necessarily depict the actual properties of each material. The results attained during this comparison can be found in Fig. 3.

Table 3. Workpiece material properties and corresponding strain hardening factor.

	A48-40B	AISI 4140	AISI 316L	Ti6Al4V
Yield strength, R_p [MPa]	276	794	280	880
Tensile strength, R_m [MPa]	400	922	570	991
Elongation at rupture, ε_b [-]	0.01	0.19	0.55	0.12
Hardness, HV [kp/mm^2]	253	275	173	353
Thermal conductivity, k_W [W/m·K]	53	43	15	7
Strain hardening factor, $D_n = R_m/R_p$	1.45	1.16	2.04	1.13

As previously published by the authors (Schultheiss, *et al.*, 2014) primarily the ductility and strain hardening of the workpiece material will influence the attained surface roughness during a general turning operation through its influence on the size of the minimum chip thickness h_{1min} as for instance depicted in Fig. 4 (Schultheiss, *et al.*, 2014).

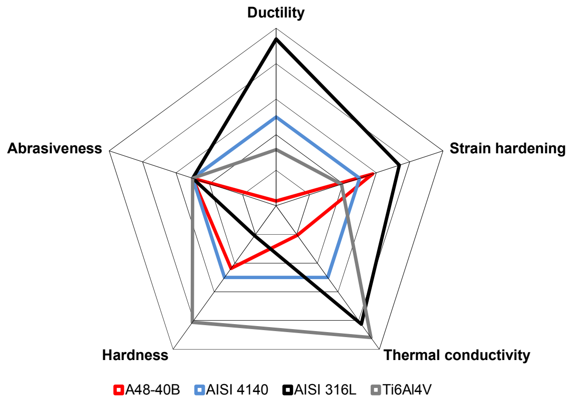

Fig. 3. Polar diagram depicting the potential machinability of each of the four materials.

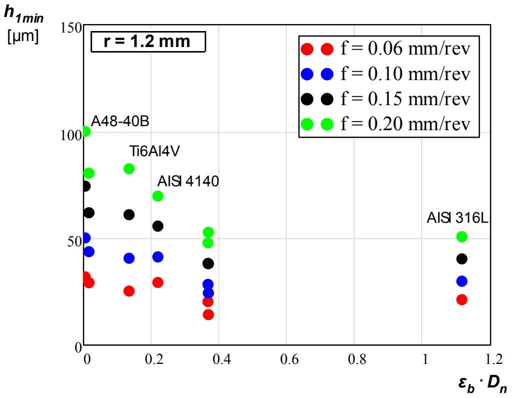

Fig. 4. Relationship between h_{1min} the product of the ductility, ε_b, and strain hardening factor, D_n.

Significant differences between the ductility and strain hardening can be noted in Fig. 3 for the investigated workpiece materials indicating that the underlying processes involved in creating the machined surfaces for these materials may be fundamentally different in nature. For instance, it could be expected that the surface obtained while machining A48-40B is attained through a more brittle fracture of the chip from the machined surface as compared to for instance the case of machining AISI 316L which could be expected to have a significantly more ductile behavior. Thus, AISI 316L is more prone to built-up edges and side-flow on the machined surface, both of which could be expected to have a detrimental influence on the attained surface roughness. Also, for a more ductile material it is possible for the machining process to better disperse the workpiece surface material over the machined surface through what is generally called ploughing and thus theoretically contributing to a better surface roughness. This phenomenon does also exist while machining more brittle materials but the influence of ploughing of the workpiece surface could generally be considered as being less pronounced in these cases due to the limited potential of plastic deformation of the material.

4. EFFECTS OF R_a ON THE CYCLE TIME

As previously stated the required surface roughness will influence the cycle time during longitudinal turning operations due to its influence on the applicable feed. A lower R_a value will require a lower feed and thus a longer cycle time. In addition, any variation of the feed will influence the applicable cutting speed in order to attain a certain tool life. The relation between the feed used during a machining operation and the cutting speed for a given tool life may be determined through for example using Colding's tool life equation (Colding, 1981), Equation 10. This model has then been further investigated by Hägglund (2013) among others. In Colding's equation K, H, M, N_0 and L are all model constants which need to be determined empirically. In the same equation T is the tool life for the investigated machining process. Colding's tool life equation makes use of the so called equivalent chip thickness h_e which according to Woxén (Woxén, 1932; Woxén, 1937) may be defined in accordance to Equation 11. An alternative model for calculating the equivalent chip thickness has also been published by Ståhl and Schultheiss (2012).

$$v_c = e^{\left[K - \frac{(\ln(h_e) - H)^2}{4 \cdot M} - (N_0 - L \cdot \ln(h_e) \cdot \ln(T))\right]} \qquad (10)$$

$$h_e = \frac{a_p \cdot f}{\frac{a_p - r(1 - \cos\kappa)}{\sin\kappa} + \kappa \cdot r + \frac{f}{2}} \qquad (11)$$

All constants in Colding's tool life equation need to be determined experimentally for each combination of tool- and workpiece material. Based on previous results for the first choice cemented carbide tools as recommended by the tool manufacturer the following values were employed as the Colding's tool life equation constants during the current investigation, Table 4.

Table 4. Examples of constants used in Colding's tool life equation for selected workpiece materials.

Material	K	H	M	N_0	L
A48-40B	6.952	-3.000	1.310	0.265	-0.029
AISI 4140	6.552	2.835	3.382	0.360	-0.078
AISI 316L	6.414	-2.243	0.501	0.242	-0.035
Ti6Al4V	5.120	-3.000	1.500	0.590	-0.128

Any variation of the required surface roughness will influence both the feed and cutting speed which in extension will influence the attained cycle time. The question thus becomes; how significant is this variation? In order to evaluate this question a hypothetical machining scenario may be considered. If assuming that a bar with an initial diameter of 50 mm should be turned longitudinally over a distance of 100 mm, as schematically illustrated in Fig. 5, the resulting engagement time could be calculated as a function of the required R_a value, tool nose radius r, and workpiece material.

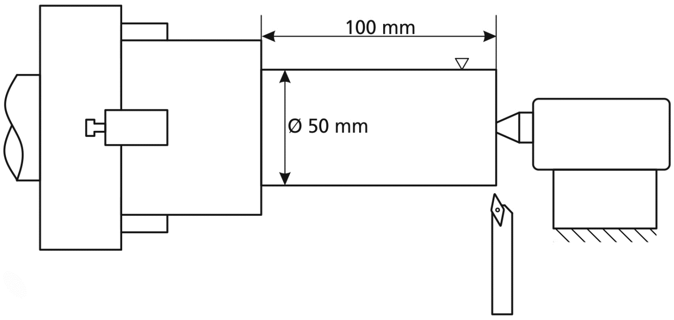

Fig. 5. Schematic illustration of the potential machining scenario.

If assuming that the workpiece is made of AISI 4140 this would result in the following feed as a function of the desired R_a surface roughness would be obtained depending on the tool nose radius r used for the specific operation, Fig. 6.

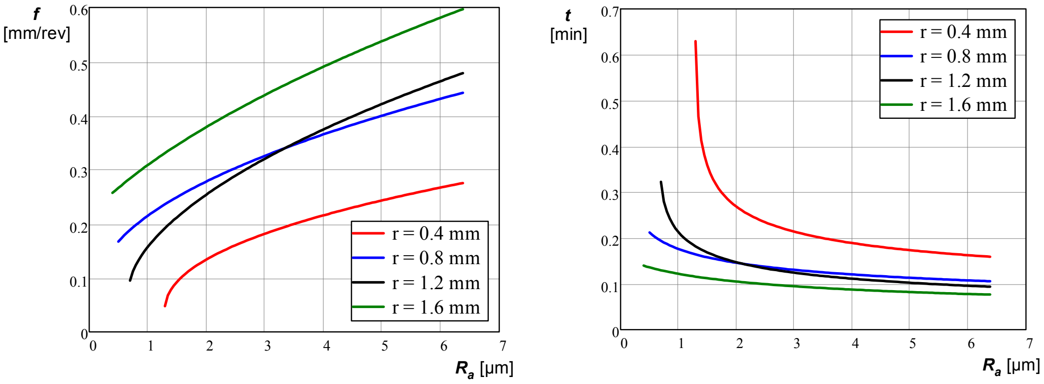

Fig. 6. Feed f (left) and engagement time t (right) as a function of R_a for different tool nose radii r while longitudinally turning AISI 4140.

Given that a tool life of $T = 15$ min is aimed for the applicable cutting speed v_c may be calculated through using Colding´s tool life equation, Equation 10. Thus, through knowledge of the feed and cutting speed for the turning process the engagement time t_i may be calculated as a function of the R_a surface roughness for each of the four investigated tool nose radii, Fig. 6. Similar calculations are possible for all investigated workpiece materials. As can be seen in the right part of Fig. 6 the required R_a surface roughness has a significant influence on the attained engagement time, especially at smaller R_a values. It is also worth noticing that even though the same surface roughness may in many cases be obtained while using different tool nose radii the engagement time for these different radii can differ substantially.

5. TOLERANCE COST ASSESSMENT

The attained production cost will vary as a function of the required tolerance for a specific part. First of all the required tolerance will determine which manufacturing method that is most suitable for achieving the desired product quality. Fig. 7 gives a brief, principal overview of how different factors during a general machining process may influence the tolerance cost. Note how the influence of these factors on the attained tolerance cost, and thus part cost, often form a complex relationship during a general machining operation, a relationship which may be hard to predict depending on circumstances. Given that machining is a suitable manufacturing method for attaining the desired product quality including the desired surface roughness for the product in question any variation of the required surface roughness will primarily influence the engagement time t_i and thus in extension the part cost k. The part cost equation, Equation 12, as formulated by Ståhl, *et al.* (2007), as well as later durther investigated by Jönsson, *et al.* (2008), has been used during this study to evaluate the variation of part cost as a function of the surface roughness criteria. Alternative cost models have also been published by for instance Colding (1978) and Alberti, *et al.* (1985). A problem with both of these models is however that they are only intended for use on machining operations. Thus, a more general model is commonly desired. Several alternative part cost models have also been reviewed by Niazi, *et al.* (2006), some of which might be applicable for the current situation after minor modifications. It can be found that changes to the required surface roughness only will influence the cycle time and tool cost during a general turning process if assuming that it is possible to achieve a stable production process under the new conditions and thus not take any variation of the scrap rate q_Q into account. Thus, the material cost may generally be ignored during this type of comparison as this cost will be the same independently of the selected tolerance. The variables used in Equation 12 as well as the following economic models are all defined in accordance to Table 5.

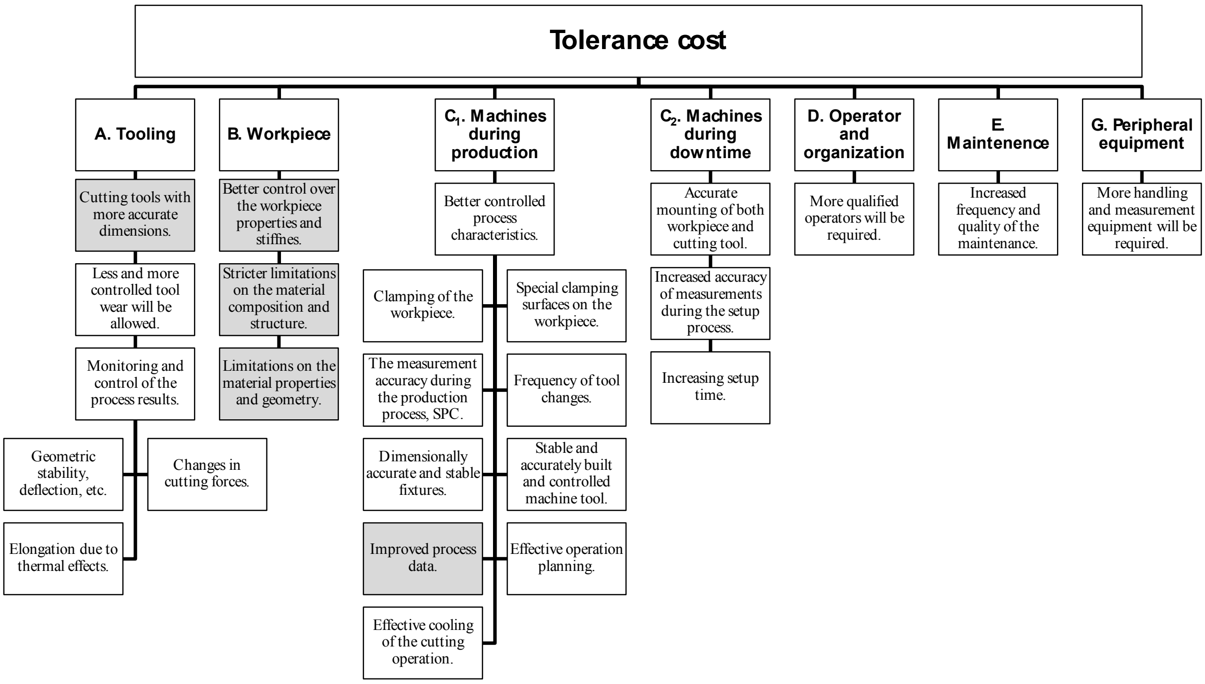

Fig. 7. Influence of varying process parameters on the tolerance cost during a general machining process. The gray areas have partially been investigated as part of the current paper.

$$k=\frac{k_A}{N_0}+\frac{k_B}{N_0}\left[\frac{N_0}{1-q_Q}\right]+\frac{k_{CP}}{60N_0}\left[\frac{t_0\cdot N_0}{\left(1-q_Q\right)\left(1-q_P\right)}\right]+\frac{k_{CS}}{60N_0}\left[\frac{t_0\cdot N_0}{\left(1-q_Q\right)\left(1-q_P\right)}\cdot\frac{q_S}{1-q_S}+T_{su}+\frac{1-U_{RP}}{U_{RP}}T_{Pb}\right]+$$
$$\frac{k_D}{60N_0}\left[\frac{t_0\cdot N_0}{\left(1-q_Q\right)\left(1-q_P\right)}\cdot\left(1+\frac{q_S}{1-q_S}\right)+T_{su}+\frac{1-U_{RP}}{U_{RP}}T_{Pb}\right] \tag{12}$$

The cycle time, t_0, during a machining process can generally be divided into two parts, Equation 13. During a machining process the cycle time generally consists of the engagement time t_i as well as addition time t_{rem} which for example include the time to correctly position the cutting tool. For the given scenario of a longitudinal turning operation the engagement time may be calculated as follows, Equation 14.

$$t_0=t_i+t_{rem} \tag{13}$$

$$t_i=\frac{l\cdot\pi\cdot D}{f\cdot v_c\cdot 10^3} \tag{14}$$

6. HYPOTHETICAL MACHINING SCENARIO

The potential influence of varying the R_a surface roughness on the attained part cost during production may be visualized through considering a hypothetical machining scenario. During this comparison the applicable cutting speed v_c was calculated through using Colding's equation, Equation 10, as previously presented. The part cost equation, Equation 14, can be simplified for the current application through assuming that the production equipment is running 100 % of the available production time. Similarly, this simplified comparison could disregard from the setup time due to its limited influence on the attained part cost, especially if considering the difference of the setup time as a function of the required R_a surface roughness. Thus, a simplified production cost model can be obtained, Equation 15. All of the required input parameters needed to calculate the part cost according to Equation 15 was in this case set according to Table 5 as based on the authors' previous experience of circumstances common for conventional machining processes. In this case it was assumed that the investigated process was running at optimal conditions. The cost of the material workpiece is not included in the current example as primarily the added cost as a result any variation of the production process is of interest. Also, during the current case it was assumed that no additional process time other than the engagement time was required, thus implying that t_{rem} = 0 min. This is of course not the case during a real machining process where factors such as tool positioning and loading of workpiece material will add to the cycle time. However, as the influence of these parameters may vary significantly depending on machining situation they have been excluded from the current comparison in order to not to mask the attained influence of the required tolerance on the production cost. During an actual machining scenario it could also be expected that the required tolerance would influence all loss parameters; i.e. q_Q, q_S and q_P. It could for example be expected that the scrape rate would be influenced by a variation of the required tolerance where typically a lower tolerance value could be expected as resulting in a higher scrap rate. A lower value of the required tolerance could also be expected as resulting in a higher downtime rate since the tools will have to be changed more frequently and more care will have to be used when setting up the machining process. Further, a lower tolerance value may also in some cases result in a production rate loss as more careful measurements may be required as part of the production process. However, as no data on these variations are currently available it was in this simplified comparison assumed that the machining process was running under ideal conditions; i.e. q_Q, q_S and q_P were all set equal to zero during this comparison.

Table 5. Variables used for calculating the part cost with hypothetical values where relevant.

Var.	Description	Unit	Value
D	Workpiece diameter	mm	50
f	Feed	mm/rev	-
k	Part cost	USD	-
k_A	Tool cost per batch	USD	-
k_B	Material cost per batch including waste	USD	-
k_{CP}	Hourly cost of machines during production	USD/h	60
k_{CS}	Hourly cost of machines during downtime	USD/h	50
k_D	Hourly operator salary	USD/h	25
k_t	Cost per cutting edge	USD	2
L	Engagement length	mm	100
N_0	Nominal batch size	Units	200
q_P	Production rate loss	-	0
q_Q	Scrape rate	-	0
q_S	Downtime rate	-	0
T	Tool life	min	15
t_0	Nominal cycle time	min	-
t_i	Engagement time	min	-
T_{PB}	Production time for a batch	min	-
t_{rem}	Cycle time excluding t_i	min	0
T_{su}	Setup time for a batch	min	-
U_{RP}	Machine utilization	-	-
v_c	Cutting speed	m/min	-

$$k = k_t \cdot \frac{t_i}{T} + k_B \left[\frac{1}{1-q_Q} \right] - k_B + \frac{k_{CP}}{60N_0} \left[\frac{(t_i + t_{rem}) \cdot N_0}{(1-q_Q)(1-q_P)} \right] + \frac{k_{CS}}{60N_0} \left[\frac{(t_i + t_{rem}) \cdot N_0}{(1-q_Q)(1-q_P)} \cdot \frac{q_S}{1-q_S} \right] + \frac{k_D}{60N_0} \left[\frac{(t_i + t_{rem}) \cdot N_0}{(1-q_Q)(1-q_P)(1-q_S)} \right] \tag{15}$$

$$k_{surf} = \frac{k}{\pi \cdot D \cdot l \cdot 10^{-2}} \tag{16}$$

Through using these values as part of the current investigation the production cost as a function of the required R_a surface roughness could be calculated for each of the investigated machining processes. For the case of r = 0.8 mm the following part costs were obtained for each of the four investigated workpiece materials, i.e. A48-40B, AISI 4140, AISI 316L and Ti6Al4V, Fig. 8. It could be noticed that the required R_a surface roughness has a significant influence on the attained part cost. However, the size of this influence varies depending on workpiece material where for instance Ti6Al4V displayed a significantly larger correlation with the surface roughness during this comparison. Another potentially more general approach for comparing the attained results could be through evaluating the cost per workpiece surface area produced, k_{surf}, according to Equation 16. Through using the results attained as part of the current research the following results could be obtained, Fig. 8.

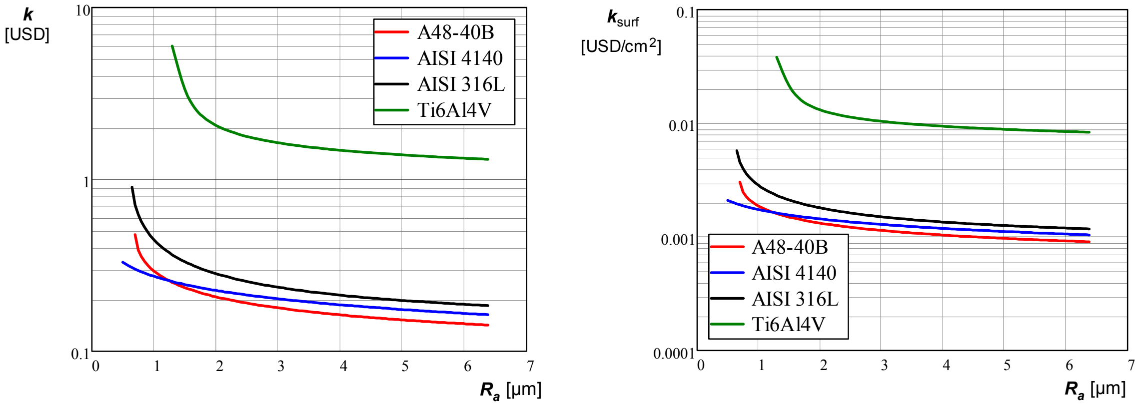

Fig. 8. Attained part cost (left) and part cost per surface area (right) for all four investigated workpiece materials as a function of R_a while using $r = 0.8$ mm.

Fig. 9 illustrates the attained results for the case of longitudinally turning AISI 4140 with a tool nose radius of $r = 0.8$ mm. As can be seen in Fig. 10 the process parameters and ultimately the part cost will vary significantly as a function of the required R_a surface roughness. This is especially true for low values of the R_a surface roughness. As exemplified in the figure through the interrupted red line the choice of surface roughness will result in a set of process parameters and as a result a part cost during a specific machining operation. In Fig. 9 it can also be noted that the part cost will increase exponentially while decreasing the required R_a surface roughness. Thus, the choice of surface roughness as part of the product development process will significantly influence the production cost.

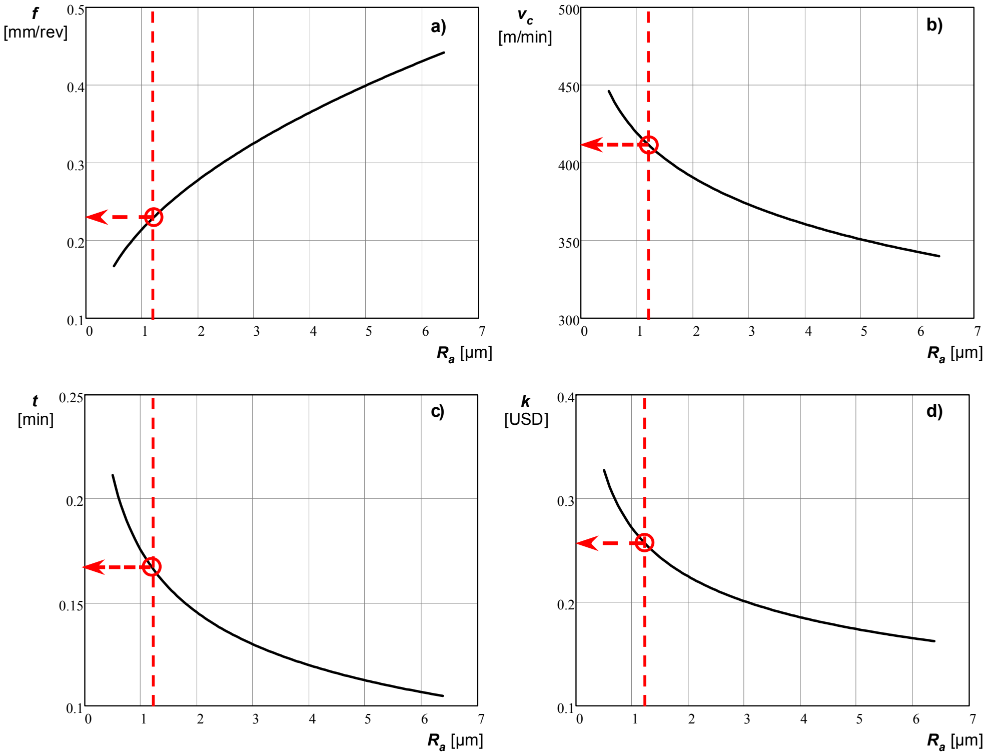

Fig. 9. Attained results for AISI 4140 at $r = 0.8$ mm when machining a part according to Fig. 5. The attained results for the requirement of $R_a = 1.2$ μm are principally illustrated by the red, interrupted line, in sequence a) to d).

7. THE PRODUCT REALIZATION PROCESS

The current method of estimating the part cost as a function of the required R_a surface roughness, workpiece material and tool geometry could be viewed as following the NEXT STEP philosophy as previously published by Ståhl (Ståhl, 2011; Ståhl, 2012b). The NEXT STEP philosophy should be viewed as potential further improvement beyond those associated with Lean Production. A central part of the NEXT STEP philosophy is the importance of expressing any change of the production process in monetary terms, thus establishing the important link between technology and economy. If considering Fig. 10 which principally illustrates the production realization process it is possible to conclude that the methodology presented as part of the current research could primarily be considered as being a part of the production development process occurring before the start of general production. It is important to note that it is in many cases beneficial, or often even a prerequisite, with some feedback from previous production of similar parts in order to ascertain whether the current manufacturing method is a reasonable choice for attaining the required tolerances. It should also be recognized that a close cooperation between product development and production development is essential during the product realization process. Although it is crucially important to consider the customer demand during the product development phase it is normally possible to significantly vary factors such as workpiece material, workpiece geometry, tolerances, etc. during the product development phase. All of these factors may have a significant influence on the attained part cost, not least through their influence on the tolerance cost as presented in the current paper.

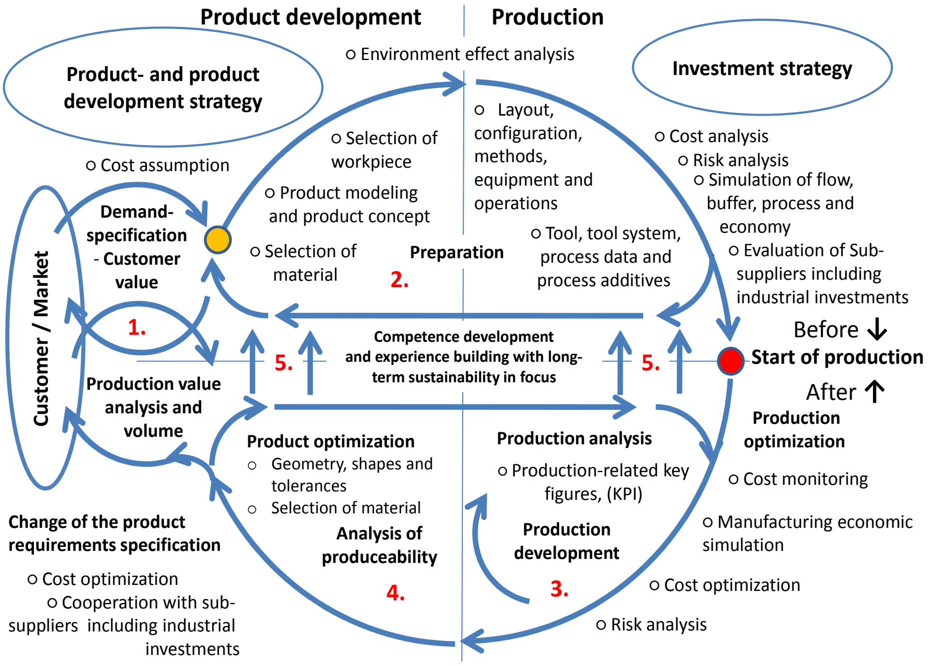

Fig. 10. Principle illustration of the product realization process (Ståhl, 2011; Ståhl, 2012).

A principle illustration of the general process employed as part of the current research may be found in Fig. 11. Note how the highest allowed R_a value is an essential input parameter attained from the product development phase. Later other factors such as workpiece material, tool- material and geometry, operation planning as well as process performance will all in turn influence the attained part cost through their influence on the tolerance cost as presented in the current paper.

8. CONCLUSIONS

Based on the results attained during the current investigation it can be found that the required R_a surface roughness does have a measurable, significant influence on the attained part cost, thus lending credibility to future use of the tolerance cost terminology. It can analytically be recognized that the required tolerance of a specific part may influence the part cost as a result of several different process characteristics as briefly visualized by Fig. 7. Further, during the current research it was found that a variation of the required R_a surface roughness will have a significant influence on the attained part cost. It was for instance found that the part cost increases exponentially as a function of a decreasing R_a surface roughness value. It was also found that correlation between required R_a surface roughness and part cost is significantly influenced by the choice of workpiece material. This highlights one of several important reasons for combining different skills from both the product- and production development phase as part of the product realization process.

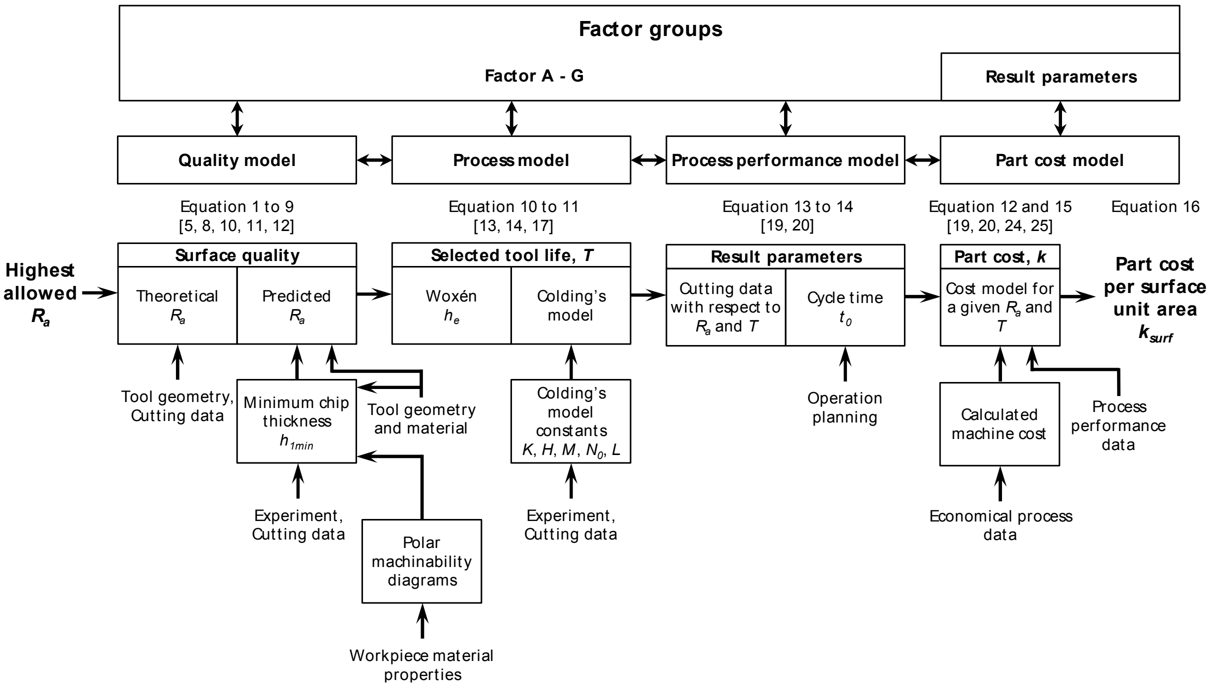

Fig. 11. Principle illustration of the methodology employed for calculating the simplified tolerance cost with respect to Fig. 7. The factor groups are defined according to Ståhl (2011).

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REFERENCES

Alberti, N., S. Noto La Diega and A. Passannanti (1985). Interdependence between Tool Fracture and Wear, *CIRP Annals - Manufacturing Technology*, **34**, 61-63.

Andersson, M. and J.-E. Ståhl (2007). Polar Machinability Diagram - a Model to Predict the Machinability of a Work Material, *Swedish Production Symposium 2007*, Gothenburg, Sweden.

Bus, C., N.A.L. Touwen, P.C. Veenstra and A.C.H. Van Der Wolf (1971). On the Significance of Equivalent Chip Thickness. *CIRP Annals - Manufacturing Technology*, **19**, 121-124.

Chou, Y.K. and C.J. Evans (1997). Tool wear mechanism in continuous cutting of hardened tool steels, *Wear*, **212**, 59-65.

Colding, B. (1978). Relative effects of shop variables on manufacturing cost and performance, *Annals of the CIRP*, **27**, 453-458.

Colding, B. (1981). The Machining Productivity Mountain and its Wall of Optimum Productivity, *Proceedings of the 9th NAMRAC*, 37-42.

Diplaris, S.C. and M.M. Sfantsikopoulos (2000). Cost–Tolerance Function. A New Approach for Cost Optimum Machining Accuracy, *International Journal of Advanced Manufacturing Technology*, **16**, 32-38.

Hsieh, K.L. (2006). The study of cost-tolerance model by incorporating process capability index into product lifecycle cost, *International Journal of Advanced Manufacturing Technology*, **28**, 638-642.

Hägglund, S. (2013). Methods and Models for Cutting Data Optimization, Doctoral Dissertation, Department of Materials and Manufacturing Technology, Chalmers, Gothenburg, Sweden.

Isaev, A.I. (1950). Microgeometry of a surface generated in turning. Academy of Science USSR, Moscow.Puhasmägi, V. (1973). Finsvarvning med hårdmetall, Finsvarvning med hårdmetall. Licentiate Thesis, Department of Mechanical Enginnering, Lund University.

Jönsson, M., C. Andersson and J.-E. Ståhl (2008). A general economic model for manufacturing cost simulation, *Proceedings of the 41st CIRP Conference on Manufacturing Systems,* 33-38.

Niazi, A., J.S. Dai, S. Balabani and L. Seneviratne (2006). Product Cost Estimation: Technique Classification and Methodology Review, *Journal of Manufacturing Science and Engineering*, **128**, 563-575.

Schultheiss, F., M. Agmell, B. Högrelius, V. Bushlya and J.-E. Ståhl (2011). Experimental Study of the Minimum Chip Thickness during the Machining of Duplex Stainless Steel. *Proceedings of the 9th International Conference on Advanced Manufacturing Systems and Technology, AMST'11*, 175-189.

Schultheiss, F. (2013). On the Machinability of Ductile and Strain Hardening Materials – Models and Methods for Analyzing Machinability, Doctoral Dissertation, Division of Production and Materials Engineering, Lund University.

Schultheiss, F., S. Hägglund, V. Bushlya, J.M. Zhou and J.-E. Ståhl (2014). Influence of the minimum chip thickness on the obtained surface roughness during turning operations. Accepted for publication in *Procedia CIRP*.

Ståhl, J.-E., C. Andersson and M. Jönsson (2007). A basic economic model for judging production development, *Proceedings of the Swedish Production Symposium*.

Ståhl J.-E. (2011). The development of NEXT STEP beyond Lean Production -The link between technology and economics with focus on sustainable developments, *Proceeding of ICA3M 2011*, Shenzhen, China.

Ståhl, J.-E. (2012a). Metal Cutting - Theories and models. Division of Production and Materials Engineering, Lund University in cooperation with Seco Tools AB, Lund/Fagersta, Sweden.

Ståhl J.-E. (2012b). NEXT STEP in Cost-based Sustainable Production Development – Cases from different production operations, *International Conference on Advances in Manufacturing and Materials Engineering (ICAMME 2012)*, Kuala Lumpur, Malaysia.

Ståhl, J.-E. and F. Schultheiss (2012). Analytical Calculation of the True Equivalent Chip Thickness for Cutting Tools and its Influence on the Calculated Tool Life. *Advanced Materials Research*, **576**, 80-86.

Ståhl, J.-E., F. Schultheiss and S. Hägglund (2012). Analytical and Experimental Determination of the R_a Surface Roughness during Turning. *Procedia Engineering*, **19**, 349-356.

Woxén, R. (1932). Theory and an equation for the life of lathe tools. *Ingenjörsvetenskapsakademins Handlingar*, Nr. 119, Stockholm, Sweden.

Woxén, R. (1937). Tool-life and balance of heat in lathe work. *Ingenjörsvetenskapsakademins Handlingar*, Nr 142, Stockholm, Sweden.

Xu, L., F. Schultheiss, M. Andersson and J.-E. Ståhl (2013). General conception of polar diagrams for the evaluation of the potential machinability of workpiece materials, *International Journal of Machining and Machinability of Materials*, **14**, 24-44.

Yeo, S.H., B.K.A. Ngoi and H. Chen (1996). A cost-tolerance model for process sequence optimisation, *International Journal of Advanced Manufacturing Technology*, **12**, 423-431.

Yeo, S.H., B.K.A. Ngoi and H. Chen (1998). Process sequence optimization based on a new cost–tolerance model, *Journal of Intelligent Manufacturing*, **9**, 29-37.