INFLUENCE OF THE WORKPIECE MATERIAL PROPERTIES ON THE CUTTING FORCES

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Abstract: This study focuses on modelling the cutting resistance as a function of the workpiece material properties. Thus, for a workpiece material the cutting resistance may be predicted from the material properties without using any experiments. The cutting resistance may then be used to determine the cutting forces, data which in turn may be used to determine appropriate process parameters and select cutting tools for a new machining operation. The model obtained produces adequate results having a variation coefficient of approximately 5 to 16 % as compared to measured values.

Keywords: Machining, Cutting resistance, Cutting forces, Material properties.

1. INTRODUCTION

Knowledge of the cutting resistance is very useful when planning a new machining operation due to the information it provides on the expected value of the cutting forces for known values of the cutting data. However, the problem facing industry and academia today is that the cutting resistance for each combination of cutting tool and workpiece material has to be determined experimentally. If the cutting resistance could be predicted before commencing production the waste of time and resources would be minimized and thus the sustainability of the machining process could be improved.

The aim of this research has been to find a method for estimating the size of the main cutting force through only using the material properties commonly available on a materials certificate. Due to the close relation between main cutting force and the cutting resistance this aim could be redefined as modelling the cutting resistance for a known set of process parameters and material properties. The model is only intended as an aid when planning the machining of a new material and does not claim to produce correct result during all possible scenarios. It should however be remembered that during many practical scenarios it is of no interest from an engineering point of view to know the exact value of the cutting resistance as long as reasonable cutting data may be estimated from the obtained approximation. It is also possible for users to improve the estimation through additional experimental investigations if thus is desired. For this potential scenario the proposed model may be used to determine reasonable starting values for the process parameters before commencing the following experimental investigation.

2. DEFINITION OF CUTTING RESISTANCE

The cutting resistance during a general machining operation is defined as the amount of energy needed per chip area to remove a chip for a certain combination of workpiece material and cutting tool. The cutting resistance, Cr, may be calculated according to Equation 1 where F_c is the main cutting force, h_1 is the theoretical chip thickness and b is the theoretical chip width.

$$Cr = \frac{F_c}{h_1 \cdot b} \qquad (1)$$

The three cutting forces are all linearly dependent upon h_1 according to Equation 2 where F_c is the main cutting force, F_f the feed force and F_p the passive force. In Equation 2 C_1, C_2, D_1, D_2, E_1 and E_2 are all constants (Vosough, *et al.*, 2013).

$$\begin{aligned} F_c &= C_2 + C_1 \cdot h_1 \\ F_f &= D_2 + D_1 \cdot h_1 \\ F_p &= E_2 + E_1 \cdot h_1 \end{aligned} \qquad (2)$$

By using Equation 2, Equation 1 may be rewritten according to Equation 3.

$$Cr = \frac{F_c}{h_1 \cdot b} = \frac{C_2 + C_1 \cdot h_1}{h_1 \cdot b} = \frac{C_1}{b} + \frac{C_2}{h_1 \cdot b} = \begin{bmatrix} Cr_1 = \dfrac{C_1}{b} \\ Cr_2 = \dfrac{C_2}{b} \end{bmatrix} = Cr_1 + \frac{Cr_2}{h_1} \qquad (3)$$

In Equation 3 both Cr_1 and Cr_2 are constants out of which Cr_1 mainly is related to the energy consumption on the rake face of the cutting tool and Cr_2 is the energy consumption on the clearance face of the cutting tool during a machining operation (Ståhl, 2012). Due to this it is possible to assume that the value of Cr_1 is primarily influenced by the workpiece material properties.

Another common method is to evaluate the obtained cutting forces through the use of the specific cutting force, defined according to Equation 4.

$$k_c = k_{c1.1} \cdot h_1^{-m_c} \qquad (4)$$

In this equation k_c is the specific cutting force, $k_{c1.1}$ is the unit specific cutting force and m_c is a constant related to the cutting force (Kienzle, 1952). Numerically $k_{c1.1}$ is approximately equal to Cr_1 with acceptable accuracy (Ståhl, 2012). This implies that the proposed model for calculating Cr_1 may also be used for calculating the specific cutting force if that is preferred. However, no model for analytically calculating m_c has thus far been established.

Previous investigations have discussed the influence of different workpiece material properties on the machining process and in particular the potential machinability of a given workpiece material. The cutting forces and thus the cutting resistance are crucial parts of the machinability concept and thus a hypothesis was formulated that the same properties used for modelling the machinability could also be used while modelling the cutting resistance. Several models for analysing the influence of different material properties on the machinability have been published through the years. The following section discusses some of the main conclusions obtained from this scientific effort.

3. INFLUENCE OF MATERIAL PROPERTIES

Several different material properties could be considered as having an influence on the machining process and in particular the cutting forces. Hastings, *et al.* (1980) discussed the influence of the workpiece yield strength on the obtained cutting forces. One important statement in their article is that it is important to assess the material properties at conditions similar to those obtained during machining operations, e.g. elevated temperatures and high strain rates. Earlier work on this subject has also been published by Katsev (1974) who investigated the influence of different workpiece material properties on the machinability for a range of different workpiece materials. He concluded that several different material properties influence the machinability of a workpiece material. Mainly he found that the ultimate tensile strength, hardness, elongation at rupture and impact toughness has a significant influence on the machinability. He also found that the size, amount and distribution of carbide particles has an influence on the machinability, a factor which might be interpreted as being equivalent to the abrasiveness of the workpiece material. Andersson and Ståhl (2007) investigated the influence of different material properties on the machinability of a certain workpiece material. They found that primarily five material properties have a major influence on the machinability of a workpiece material. These five material properties were the ductility, hardness, thermal conductivity, strain hardening and abrasiveness of the workpiece material. These material properties closely resemble those investigated by other authors and thus these properties were considered as suitable input data for the current investigation. The polar diagram method has also been further investigated by among others Xu, *et al.* (2012), Pajazit, *et al.* (2011) and Olovsjö, *et al.* (2012), all of which appear to validate the potential use of the method. An example of a principle polar diagram for illustrating the potential machinability as first proposed by Andersson and Ståhl (2007) is given in Fig. 1.

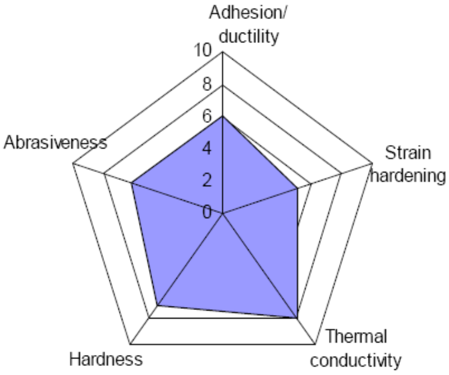

Fig. 1. Principle polar diagram for evaluating the potential machinability of a workpiece material (Xu, *et al.*, 2012). A higher value on any axis indicates a decrease of the machinability.

In the model developed by Andersson and Ståhl (2007) the elongation at rupture is used for measuring the adhesion of the workpiece material. Further, the strain hardening was calculated as the ratio between ultimate tensile strength and the yield strength and the thermal conductivity was described by the workpiece thermal conductivity. The hardness was in this case measured as the Vickers hardness HV. As stated by Xu, *et al.* (2012) it is still not determined how to numerically evaluate the abrasiveness of a workpiece material. One hypothesis currently under investigation is whether or not it is possible to use a large number of micro or nano hardness measurements for determining the abrasiveness of a specific material. However, this far no conclusive results proving this hypothesis have been presented.

It has previously been shown that a high level of the ductility of a workpiece material correlates to a strong adhesion between the workpiece material and the cutting tool resulting in a lower machinability for the specific material. It may generally be considered that a high level of strain hardening implies that more energy is required for chip formation and thus resulting in higher cutting forces and a higher cutting resistance.

Heat is generated by the machining process through the plastic deformation of the workpiece and through the friction between the cutting tool and the workpiece material. In most cases a high level of the thermal conductivity of the workpiece material is considered as beneficial as this help to rapidly conduct heat away from the cutting zone and thus decrease the temperature in the cutting zone. A decrease of the temperature in the cutting zone will result in decreasing tool wear. However, a high temperature often leads to a lower strength of the workpiece material and thus decreasing the cutting forces. From this vantage point low thermal conductivity appears could have a beneficial effect on the cutting forces even though it is unclear how this will influence the overall machinability due to the increased tool wear. The conclusion that may be drawn from this discussion is that it is often favourable to have a balanced level of the thermal conductivity in relation to the tool material used for a specific machining operation.

It can be stated that the hardness of the workpiece material has a large influence on the cutting resistance and thus is an important factor to include during this study.

Abrasiveness is a material property which is hard to define since many tests commonly used to investigate this property, such as pin-on-disc tests, only describe the relation between two different materials rather than the property for one specific material. It may however be concluded that the abrasiveness has a large influence on the tool wear. Even though the abrasiveness does influence the machinability of a workpiece material the authors found it unlikely that this factor would have any major influence on the cutting forces and thus the cutting resistance. The abrasiveness property was thus not included in the model for calculating the cutting resistance. This assumption should however be further investigated in the future when a reasonable method for determining the abrasiveness of a single material has been determined.

Even though the model published by Andersson and Ståhl (2007) primarily was intended for describing the machinability it is conceivable that the same material properties may be used for modelling the cutting resistance due to the close relation between these factors as indicated in section 2. The following section discusses a proposed model for calculating the cutting resistance as based on these properties.

4. PROPOSED MODEL FOR CALCULATING Cr_1

By assessing the previously published articles it was theorized that four different material properties could be used in order to model the cutting resistance. These four properties are the hardness, yield strength, elongation at rupture and thermal conductivity. It is conceivable that other material factors influence the cutting resistance as discussed in the previous section. However, out of the different variations tested during this study these four properties produced the smallest error. A goal pursued by the authors was also to include only material properties commonly found on a material certificate and thus to simplify the use of the proposed model.

Several different models could be created by using these parameters. After some attempts of using different types of functions it was found that the relation found in Equation 5 produced the lowest variation coefficient and thus was conceived as the most appropriate for modelling Cr_1. The generic and repetitive character of this equation was also thought of as suitable due to the large variation of material properties and their varying influence on the cutting resistance for different workpiece materials. In the model the four material properties hardness HV, yield strength R_p, elongation at rupture ε_b and thermal conductivity k combined with eight constants (α, β, δ, γ, η, ν, ξ and ω) were used according to Equation 5. By determining the value of Cr_1 through experimental investigations as well as knowledge of the material properties for several different workpiece materials it is possible to determine all eight constants by minimizing the difference between the Cr_1-value generated by the model as compared to the experimentally obtained values. In this study the Levenberg-Marquardt algorithm (Levenberg, 1944; Marquardt, 1963) were used in order to obtain the numerical values of all constants.

$$Cr_1 = \alpha \cdot HV^{\delta} + \beta \cdot R_p^{\nu} + \gamma \cdot \varepsilon_b^{\eta} + \xi \cdot k^{\omega} \qquad (5)$$

It might be debated which unit should be used for each of the material properties and it is possible to make a strong case towards only using SI units. However, as one of the goals of this research was to create a model which is easy to use in a practical scenario it was chosen to use units which are commonly used for each material property respectively. For all analysis presented in this article the following units were used for the material properties including Cr_1; hardness HV [kp/mm^2], yield strength R_p [MPa], elongation at rupture ε_b [%], thermal conductivity k [W/mK] and Cr_1 [N/mm^2].

5. ISO MATERIAL GROUPS

As a way of sorting materials with regards to their metal cutting properties ISO 513:2004 (2004) has determined 6 different material groups; P, M, K, N, S and H. Each of these contains a specific type of materials which are thought to behave similarly during metal cutting operations. Table 1 describes the different material groups in more detail.

Table 1. Standardized ISO material groups, ISO 513:2004 (2004).

ISO	Description
P	All kinds of steel and cast steels except stainless steels with austenitic structure
M	Stainless austenitic and austenitic/ferritic steel.
K	Grey cast iron, cast iron with spheroid graphite and malleable cast iron.
N	Aluminium and other non-ferrous materials.
S	Heat resistant special alloys based on iron, nickel, cobalt and/or titanium.
H	Hardened steel and cast iron materials.

Although the materials included in each material group may differ significantly they still display similar properties when compared to the other material groups and it could thus be argued that a better model would be obtained when modelling the Cr1 for each of these material groups independently. This approach in combination with that of modelling all materials as one entity has thus been investigated. However, from a practical standpoint it would simplify the model for the user if only one set of constants were used independently of the type of material. It could also be discussed if ISO 513:2004 is an appropriate method for dividing different types of workpiece materials or whether or not any better method does exist.

6. OBTAINED RESULTS WHEN MODELLING Cr_1

Experimental data on the cutting resistance and material properties were mainly obtained from two sources (Ståhl, 2012; König, *et al.*, 1982). Totally, the cutting resistance of 98 different materials were investigated. This set of data made it possible to determine the model constants according to Equation 5. It should be noted that the rake angle varied somewhat for some of the machining cases reported by these sources. This could result in an error of the obtained results which need to be considered while evaluating the obtained results. Further, it could be argued that the amount of data points in some cases is insufficient given the use of an 8 degrees of freedom model. However, as of current the limited amount of published data of this type made it difficult to include more data points; thus, it should be recoginzed that the model could be imporved even further in the future through the inclusion of more data points.

In order to evaluate how well the obtained model values correspond to the known values of Cr_1 the obtained coefficient of variation V were calculated according to Equation 6. In Equation 6 n is the number of materials investigated. The index input indicates experimental values attained from the previously cited sources (Ståhl, 2012; König, *et al.*, 1982) and the index model indicates values obtained through using the proposed model.

$$V = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Cr_{1,input} - Cr_{1,model}}{Cr_{1,input}}\right| \qquad (6)$$

As well as trying to create a general model for all materials it was also attempted to model each ISO material group individually. This approach was based on the notion that there exists a significant difference between the different material groups and thus a smaller error would be obtained if each material group was modelled independently. As may be seen in Table 2, the variation coefficient for modelling all 98 materials as a single entity was roughly 13 %. Also, the variation coefficient may in some cases be significantly smaller if each ISO material group is modelled independently. For example the variation coefficient when only modelling ISO P materials was only approximately 5 %. However, larger variation coefficients were also obtained for example for ISO M and ISO S materials with variation coefficients of approximately 13 % and 16 % respectively. When comparing the results for the different ISO material groups the result for ISO material group K and H should be ignored. This due to that the Cr_1-value was only known for 3 and 4 materials, respectively, for these material groups during the present study. Thus, a model containing 8 constants is completely inappropriate for modelling this few known values.

From the results obtained during this study it is possible to conclude that for some ISO material groups an advantage may be obtained by only modelling the group independently of the other material groups. However, in general it may be found that the model for all workpiece materials generates comparatively good results and it could thus be speculated that this model may be appropriate during all scenarios, independent of workpiece material.

As may be seen in Table 2 the model gives an error of more than 10 % in several cases including when modelling all materials as one entity. For the case of modeling all materials as one entity it was found that with a 90 % probability the attined error ε, Equation 7, will be in the range $-26\ \% \leq \varepsilon \leq 19\ \%$. If instead only consdidering ISO P materials the error will instead be in the range of $-16\ \% \leq \varepsilon \leq 7\ \%$ with a 90 % probability. Part of the reason for this error is belived to be variations of the triboligical characteristics on the rake face of the cutting tool while machining the different materials as well as potential discrepencys between properties of the material sample used for evaluating the material properties and the material used during the machining process. The attained model error is generally too large to be ignored but at the same time it is still sufficiently small for the user to be able to give a good approximation of the Cr_1-value. The obtained results should thus only be viewed as an approximation of the Cr_1 cutting resistance. If more accurate results are needed further experiments must be performed for the specific machining case. However, the obtained accuracy is often sufficient when investigating the machinability of a new workpiece material in order to find appropriate starting conditions. It is then imperative that these starting conditions are improved to better suit the current machining operation as based on the obtained results from the initial machining setup.

Table 2. Obtained errors when modelling different ISO material groups.

ISO material group	*V* [%]	Number of materials
All materials	12.8	98
P	5.2	56
M	13.1	14
K	N.A.	3
N	12.6	11
S	16.2	10
H	N.A.	4

$$\varepsilon = \frac{Cr_{1,input} - Cr_{1,model}}{Cr_{1,input}} \qquad (7)$$

The values of the obtained model constants may be found in Table 3. Several interesting characteristics of the cutting resistance Cr_1 may be discerned by studying Table 3. For example it may be observed that the α constant is positive for all material groups signalling that an increase of the hardness HV increases the Cr_1-value which was expected. It may also be noted that the value of the δ constant is close to 1 implying that Cr_1 is almost linearly dependent upon HV. It should also be noted that the v variable is comparatively small for most materials implying that the yield strength has a comparatively small influence on the Cr_1-value. It should however at the same time be noted that the v variable is considerably larger for certain material groups. This is thought to reflect the influence on the strain hardening properties of the different material groups and the influence of the strain hardening on the cutting resistance. The constants γ and η are positive for all material groups implying that an increase of the elongation at rupture ε_b will increase the Cr_1-value.

Table 3. Obtained model constants.

Property	Constant	All	P	M	N	S
HV	α	12.8	13.8	12.4	10.0	9.6
	δ	0.79	0.80	0.78	0.75	0.72
R_p	β	-13.0	-20.7	-2.8	-63.1	4.2
	v	0.07	0.50	0.74	0.35	0.65
ε_b	γ	543	679	542	806	564
	η	0.15	0.16	0.12	0.04	0.16
k	ξ	-3.10	-2.60	5.37	-1.65	7.50
	ω	1.09	1.11	1.31	0.99	1.44

At the beginning of this study it was implied that an increase of the thermal conductivity k would be beneficial for lowering the cutting resistance for all materials. As may be observed in Table 3 this is true for almost all material groups by observing that the ξ constant is smaller than 0. However, an exception may be noted for the ISO M and S material groups which display an opposite relationship. This exception is hard to explain but one possible explanation may be that the comparatively low thermal conductivity for these groups of materials will decrease the heat dispersion from the secondary deformation zone where the chip is deformed against the rake face of the cutting tool into the primary deformation zone and thus decreasing the required cutting forces. Also, both of these material groups, ISO M and ISO S, display a pronounced tendency towards adhesion between the workpiece material and cutting tool. As a result elevated temperatures may be desirable for minimizing the adhesion and thus also minimizing the cutting resistance. Fig. 2 illustrates the differences between the measured Cr_1-values obtained from literature and the Cr_1-values obtained from the model when modelling all materials as one entity as well as each material group individually.

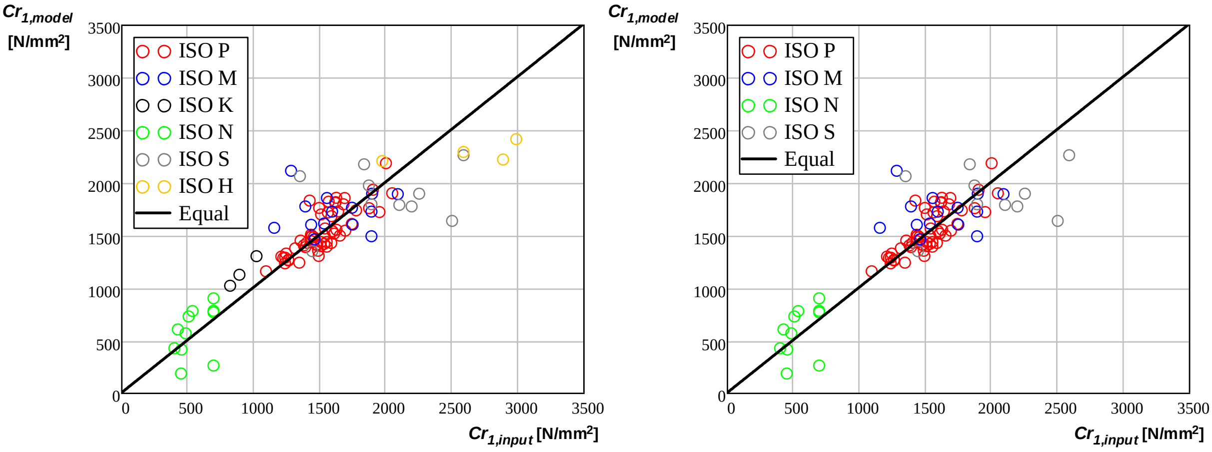

Fig. 2. Comparison between modelled and measured Cr_1-values while modelling all materials as one entity (left) as well as each ISO material group individually (right). The solid line illustrates $Cr_{1,input} = Cr_{1,model}$.

As may be seen in Fig. 2 the model appears to depict the measured values comparatively well although some deviations may be found. This deviation is particularly clear for certain materials included in the ISO material group H and in some cases also ISO material group M and S.

Another way of comparing the obtained model with the measured Cr_1-values is by comparing the relative difference as may be seen in Fig. 3. From the results illustrated in Fig. 3 it may be concluded that the proposed model is especially well suited for ISO P materials with comparatively small errors. The model prediction is significantly worse for some other material groups such as for example ISO M, ISO S and ISO H. A reason for this could be that significantly more ISO P materials were included in the study and thus the obtained model constants could be better suited for these materials. In addition the influence of the workpiece material properties on Cr_1 may in some cases deviate for these materials as compared to the more common ISO P materials. This supports the notion that for increased accuracy every ISO material group should be modelled separately if sufficient amount of input data is available. However, given the accuracy of the general model according to previously it is the author's opinion that the model for modelling all material groups as one entity is sufficient for most practical scenarios as greater accuracy of Cr_1-value may not assist in finding suitable process parameters when commencing production.

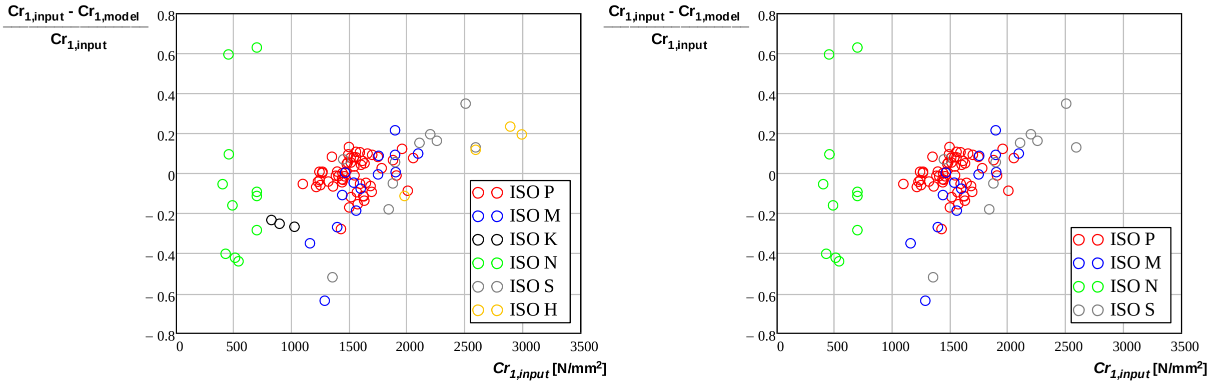

Fig. 3. Relative comparisons between modelled and measured Cr_1-values while modelling all materials as one entity (left) as well as each ISO material group individually (right).

7. DISCUSSION AND CONCLUSIONS

The model for calculating the cutting resistance Cr_1 as a function of the workpiece material properties appear to produce adequate results even though a small error is obtained. Although the error when modelling all ISO material groups simultaneously results in a comparatively small error it could still be assumed that better results should be obtained when modelling each ISO material group independently due to the inherent similarities of the material properties within each material group. If using all materials when modelling the Cr_1 cutting resistance the obtained error is small but not negligible. It should thus be pointed out that the model presented should only be used in order to estimate the cutting resistance before the machining process.

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