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STUDY OF COMBINED MACHINING PARAMETERS ON 3D ROUGHNESS BEHAVIOUR IN MOULDS AND DIES

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ABSTRACT

In order to process materials with special characteristics (e.g. brittleness, hardness and stiffness), high-speed machining (HSM) has gradually become one of the most popular metal cutting and machining methods. In the die-mould manufacturing industry, HSM is mainly used for workpiece machining. By applying HSM technology[1], it is possible not only to obtain specific surface roughness parameters, but also to improve surface quality generally. This is because the technological parameters of the machining have an impact not only on surface quality parameters such as surface texture and roughness, but also on surface micro-hardness.[2] This paper contains detailed results on how high-speed milling impacts on 3D surface texture and roughness parameters. The ISO25178 standard of geometric product specification was used to characterize surface roughness. This paper also offers a comprehensive review of how HSM impacts on industry and the surface micro-hardness with regard to particular materials. Carefully designed experiments were conducted, varying technological parameters, which were recorded along with the relevant 3D roughness parameter measurements. Significant conclusions are based on the compilation of statistical models, to find differences between groups of means. Analysis of variance was applied in this research, using R-commander software for ANOVA analysis. This paper also proposes initial recommendations for mould and die manufacturers to deploy HSM to improve the machining process and surface quality.

1. INTRODUCTION

Surface topography measurements are an important area in characterization of machined steel surfaces. If in the past 2D surface roughness measurements were sufficient to describe the machined surface, there is nowadays greater potential to improve machining processes with information obtained from 3D surface topography measurements. Wide ranging factors of influence, which it is necessary to take into account, make it very difficult to select the most appropriate operating conditions.[3] Several studies have already been conducted, to identify how technological parameters affect surface topography parameters.[3],[4] For the most part, such research only considers what has been generally established in science and uses general topography parameters such as S_a – average roughness S_q – root mean square roughness and S_t – max. peak-to-valley roughness.[5] These parameters are inadequate to describe machined mould surfaces. Several other, more appropriate surface texture parameters can be used for mould and die manufacturing.

Our research focuses solely on the most correlative parameters, which are specific to this industry and mathematically proven. S_a – arithmetic mean surface height, S_{tr} – texture aspect ratio, S_{ku} – kurtosis of the scale-limited surface and S_{vi} – valley fluid retention index.

Machined material surface quality parameters involve not only surface texture, but also the micro-hardness of the machined surface and geometrical surface and shape errors. Therefore the research also had to include mathematical analysis of how the high-speed machining technological parameters influence surface micro-hardness, measured before and after sample processing. Geometrical surface deviations are dependent on machining technological parameters and thus also have to be taken into account.[6]

2. EXPERIMENTAL PROCEDURE

Initially, several samples were machined using high-speed milling on three different die-mould materials (C45 - 1.1730, 40CrMnMo - 1.2312 and BT1-0). In these samples, such parameters as cutting depth, strategy, overlap and tool-nose radius were modified.

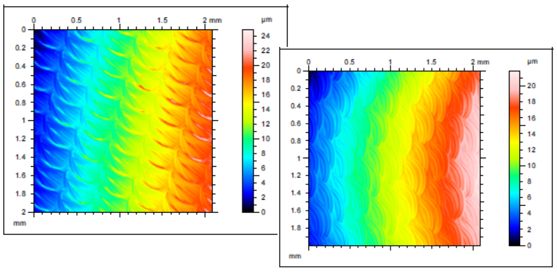
After confirming the influence of these parameters (Fig. 1), both in isolation and combined, the relevant effect of other variables not taken into account so far was observed. The variables for sample No. 3 and 5 are represented in Table 1.

Table 1

Technological parameters for sample Nos. 3 and 5

Sample Nr.	*Strategy*	*Overlap, mm*	*Feed, mm/min*	*Mode*
3	*LP*	*0.1*	*12566*	*Up*
5	*CP*	*0.1*	*12566*	*Down*

Inter alia, the relation between up-and-down machining, overlap and tool-nose radius variables were analyzed. An appropriate number of samples were machined to demonstrate the influence of these new variables. A new type of material was then added (Toolox 33).



a) b)

Fig. 1. *Marks and traces in samples nº 3 (a) and nº5 (b), top view. Material: Toolox 33*

3. APPROACH

To provide useful recommendations for die and mould manufacturers, it is important to use relevant cutting technological parameters in accordance with the die mould manufacturers' practices. In the experiment however, the materials used were chosen for their mechanical properties from suggestions from the plastic part moulding industry and die-mould manufacturers. Therefore information will be required from further investigation before it is applied in manufacturing. In the first stage of this research, two different types of materials were chosen, each with different mechanical and chemical properties. Both materials are commonly-used industrial die-mould steels. The first is 1.1730 moulding steel, a surface-hardened steel with a tough core, suitable for die-mould manufacturing. This steel has lower tensile strength and lower hardness than other materials used in die-mould manufacturing. The second material is a widely used 1.2312 die-mould steel, with higher tensile strength and hardness, but with lower elongation properties. It has higher resistance and is appropriate for mechanical treatment and machining.

To conduct extensive and more accurate research into the influence of the materials' mechanical properties on 3D surface topography parameters, it was decided to introduce an additional material with a different chemical composition and mechanical properties – unalloyed titanium.

In the second stage of this research, the authors enhanced the number of machined samples with another new material, Toolox 33. This is a die-mould steel with similar mechanical properties to 1.2312 steel, but with a different chemical composition.

All of the material mechanical properties and chemical compositions are shown in Table 2.

Table 2

Chemical and mechanical properties of the materials

Material	***Chemical composition***	***Tensile strength - Yield strength - Elongation – Hardness***
Mould Steel 1.1730	0.45C – 0.27Si – 0.7Mn	640N/mm^2 – 340N/mm^2 – 20% - 190HB
Mould Steel 1.2312	0.4C – 0.4Si – 1.5Mn – 0.03P – 0.08S – 1.9Cr – 0.2Mo	990N/mm^2 – 860N/mm^2 – 15% - 280-325HB
BT1-0 Grade 2	0.18Fe – 0.07C – 0.1Si – 0.04N – 98.61/99.7Ti – 0.12º – 0.01H – 0.3Mo	400-450N/mm^2 - 300-420N/mm^2 – 30% - 210HB
Toolox 33	0.24C – 0.11Si – 0.8Mn – 0.01P – 0.02S – 1.2Cr – 0.3Mo	980N/mm^2 – 850N/mm^2 – 16% - 300 HB

The GENTIGER GT-66V-T16B HSM high-speed milling (HSM) machine was used to machine all the samples in this research. It is equipped with a Mitsubishi type VC2ESB spherical ball-end milling tool. The 4mm radius ball nose is coated with Al, Ti and N. The milling tool was adjusted at 90º to the work surface.

To analyze the influence of the technological parameter it is necessary to apply different combinations of cutting conditions on each of the chosen material samples. Therefore, each material sample was divided into 16 subsamples, which were machined with different cutting parameters. The chosen cutting parameters are:

Cutting strategy:

1) Linear Path (LP) - the tool movement on the material is straight and one-way.
2) Circular Path (CP) - the tool moves on the surface in a spiral path outwards from the centre.
3) Two Linear Paths (TLP) – combination of two linear paths, one along the X axis and the other along the Y axis.

Cutting overlap: Two different overlap values were chosen according to the peak heights. The chosen values are 0.05 and 0.1mm.

Feed speed: Feed speed is potentially one of the most important technological parameters, as in conventional milling. The feed rates were chosen in accordance with the tool manufacturer, who recommended using 3 different linear feeds:

a) 2,513mm/min (0.08mm/tooth);
b) 6,283mm/min (0.2mm/tooth);
c) 12,566mm/min (0.4mm/tooth).

To ensure the correct machining of the titanium, the feed speeds were altered:

a) 587mm/min (0.08mm/tooth);
b) 1,466mm/min (0.2mm/tooth);
c) 2,933mm/min (0.4mm/tooth).

Milling mode: As in conventional milling, there are two possible milling modes – up-milling and down-milling. For up-milling, the tool rotation direction is opposite to the feed direction. In down-milling, the tool rotation is the same as the feed direction. Both milling modes were used for all selected machining strategies and feed types.

All other technological parameters were kept constant, in accordance with the die-mould manufacturers' recommendations and HSM technology.

Cutting depth: The cutting depth was kept constant at 0.3mm, to ensure part finishing conditions.

Spindle speed: The spindle speed was maintained at 16,000 rpm as recommended by the tool manufacturer and HSM technology, to ensure the correct chip formation and appropriate machining processes.

Surface texture measurements

The first 3D surface topography measurement stage was conducted at Riga Technical University, Latvia. The results were obtained with the Taylor Hobson Form Talysurf Intra measuring device. It provides simultaneous measurement of surface texture parameters, dimensions, form and surface roughness. The device is equipped with Talymap expert analysis software. Some 4 samples of the Toolox 33 material were also measured on this device to compare the results, check the standard deviations and absolute errors. The second measurement stage took place in the Faculty of Mechanical Engineering at Tallinn University of Technology, in cooperation with associate professor Fyodor Sergeyev. All the Toolox33 material samples were measured on the Bruker Contour GT3 optical microscope (Fig. 2.), equipped with Vision64 software.

Fig. 2. *Measurements taken using the Bruker Contour GT3 optical microscope*

This measuring method is quicker than the contact method using the Taylor Hobson device and provides more precise results, excluding errors caused by needle shape defects (Fig. 3.).

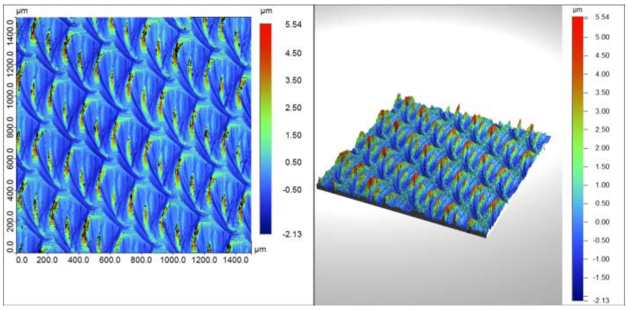


Fig. 3. *Marks and traces in sample nº 3 Material: Toolox 33 measured by the Bruker Contour GT3*

4. DATA ANALYSIS

In the first stage, the measurements were taken for all 16 subsamples of the 3 material types. For the additional material, several samples were measured, to conduct additional analysis on the influence of the material's mechanical properties on surface topography. The obtained results were sorted by group, according to the surface parameter they describe. These groups were then subjected to an analysis of mathematical correlation. The correlation matrix of *n* random variables was then drawn up. The matrix included a set of 3D roughness parameters from each group, to determine the most relevant HSM parameter for each group.

To conduct the analysis and determine the technological parameters' influence on 3D surface roughness parameters, a multifactorial analysis of variance (ANOVA) was undertaken between all types of materials. New values were introduced into the analysis, with technological parameters being replaced by factorial values, as required by the method of analysis. These values were replaced by two or three factors. In this analysis, the surface parameters were used as a response function of technological parameter's interaction with the analysis function. R-commander mathematical analysis software was used to perform the mathematical verification.

In the first stage of this research, three types of materials were compared in terms of the dependence of their surface topography behaviour on the cutting parameters. A graphical spreadsheet analysis was prepared using the ANOVA results. The graphical spreadsheet shows the trend line coefficients of the polynomial regression equation with argument x. The analysis showed that some technological parameters, such as the cutting tool strategy type, have a significant influence on surface texture parameters, although this is not a major contributor (Fig. 4.). Almost all other chosen impact factors had a higher influence rate in HSM.

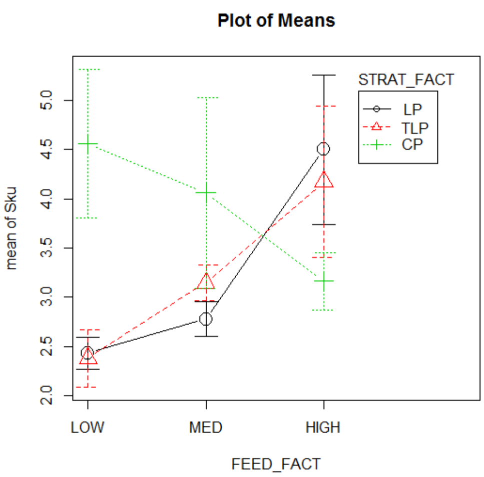


Fig. 4. *Plot of means for the parameter S_{ku} of strategy and feed influence*

This parameter is affected by strategy type up to 2.2 times, depending on the strategy type, comparing the strategy and feed factor influence. Only the parameter S_a value is lower on average than the other texture parameter values, which was generated by applying a circular path strategy type. All other chosen 3D surface texture parameter values are higher with a lower feed factor, even for Titanium samples. It can be seen in Fig.4. that by using the circular path strategy, the influence of the feed speed is absolutely different – increasing the feed speed decreases the S_{ku} value. This may be caused by the chaotic distribution of the surface texture (peaks) over the measured surface area, which is generated by the circular strategy type.

Also the overlap influence was detected as an insignificant cutting parameter. Of course, this parameter is predicative, in that increasing the overlap value increases the peak height (Fig. 5). Roughness parameter distribution is similar for both overlap values, but they are dependent on material type. In the case of previously machined materials, the average roughness difference was higher than with the material Toolox33.

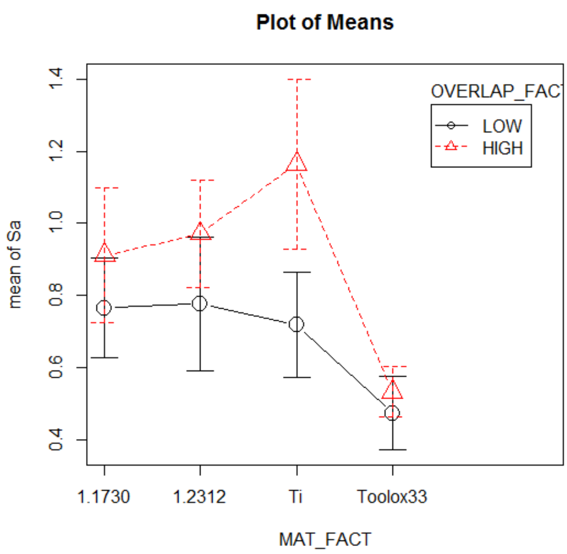


Fig. 5. *Plot of means for parameter S_a of overlap and material influence*

Mathematical analysis confirms that the material factor is a more important influence than overlap (see Fig. 6.).

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> Anova(AnovaModel.5)
Anova Table (Type II tests)

Response: Sa
                     Sum Sq Df F value  Pr(>F)
MAT_FACT             1.6854  3  2.8537 0.04527 *
OVERLAP_FACT         0.7044  1  3.5780 0.06373 .
MAT_FACT:OVERLAP_FACT 0.3280  3  0.5553 0.64673
Residuals           11.0248 56
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Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.'
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Fig. 6. *Mathematical analysis of material factor and overlap influence*

Relative to the other parameters, we can see in Fig. 6 the plot of means for tool feed. In the case of overlap influence, increasing the feed rate should increase the topography parameters. This is true for parameters S_a, S_{ku} and S_{vi}, S_{tp}, but not for S_{tr}, since with this parameter, at the highest speeds, the cutting marks and topography texture aspect are better preserved by the direction and behaviour, but at lower speeds, the machined surface is more isotropic. The S_a parameter has a different distribution according to types of materials and feed rates. Materials with lower tensile strength at lowest feed rate have higher texture parameters, whereas with increased material mechanical properties, the surface texture parameters diminish. (Fig. 7)

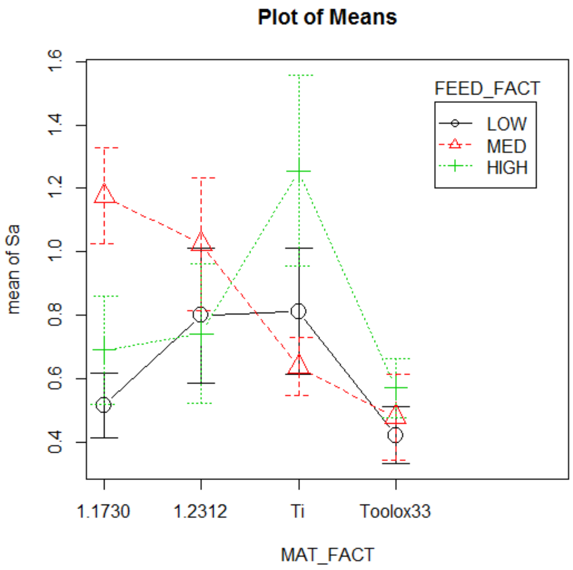

Fig. 7. *Plot of means for parameter S_a for feed rate and material influence*

This conclusion provides real data for manufacturers.

As mentioned above, the number of samples was enhanced to prove the results achieved in first stage of research. As the figures show, the results for the different materials sometimes diverge up to 6 times, depending on the influence of the material's mechanical properties on cutting forces.

The influence of the milling mode (up/down) can be seen in Fig. 8. As shown, the milling mode significantly affects the surface parameters and the surface texture parameters are distributed differently for each material.

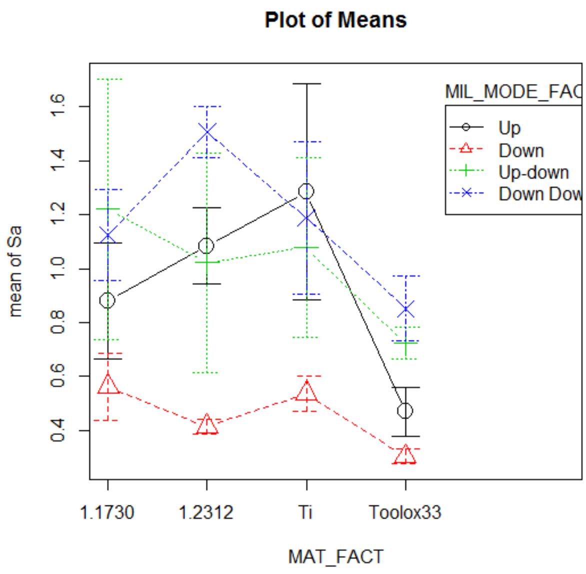

Fig. 8. *Plot of means for parameter S_a of milling mode and material influence*

The down-milling mode generally has the best influence on cutting processes, the best chip formation and lowest vibrations, as shown in Fig. 8., surface texture parameters are growing together with material mechanical properties In this case, material Toolox33 is different, because mechanical properties are similar to material 1.2312. In most cases, samples of material Toolox33 have the lowest texture and the best surface roughness parameters. Thus the material is a major influence, although this may not only be related to material mechanical properties, but also to the material's chemical composition and manufacturing nuances.

5. CONCLUSIONS

After analyzing the results, the authors identified which factors had the most impact on machining and surface texture parameters. The following conclusions were obtained:

1. The up/down milling mode is the most relevant parameter for 3D surface roughness. The correct chip formation and acceptable volume of removed material reduce the process forces and vibrations. The down milling mode provides the lowest surface texture parameters S_a and S_{ku} – for mould and die materials. Parameter S_{vi} and S_{tr} reaches the lowest values

by using TLP strategy with the appropriate milling mode.

2. Based on the mathematical ANOVA multifactorial analysis results, the second most significant influence on texture parameters is the material (or the material's mechanical properties). Toolox 33, which has different mechanical properties and chemical composition, confirmed the arguments of the material's influence on surface texture parameters. On observing the results, Toolox33 is the most appropriate material to use for mould and die manufacturing with HSM.

3. Analytically, the machining strategy is the third major factor of influence in HSM. The differences between texture parameters can be up to 2.2 times greater. The lowest texture parameter values were obtained by using circular path (CP) and linear path (LP). Both were used in combination to produce mould and die workpieces. Two linear paths (TLP) milling has a negative effect on the material surface roughness and probably also on mechanical properties.

4. Small overlaps and small cut feeds lead to the concentration of the cutting zone around zero radiuses. The negative effect of these phenomena masks the results.

To prove these phenomena, as well as the TLP effect on surface texture and mechanical parameters, surface micro-hardness measurements and analysis are required. These surface micro-hardness measurements are still in progress.

6. REFERENCES

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