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The Influence of High-Speed Milling Strategies on 3D Surface Roughness Parameters

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Abstract

Nowadays in die-cast manufacturing high speed milling are used to increase quality, accuracy and speed of material processing, also to reduce processing costs and save machining time. This paper is devoted for research of high-speed processing regimes impacts and their effect on the surface roughness quality of the machined material and 3D surface parameter values. This paper contains recommendations for die-cast manufacturers, deploying HSM, to improve machining process and obtain required surface quality. Analysis of variance methodology is used in this research. Research identify the most appropriate HSM regimes, that most important is chosen material type or material mechanical properties, influencing kurtosis of the scale-limited surface (Sku) and height of the bearing area ratio curve (Stp). Feed rate is most significant for texture aspect ratio (Str) and strategy type – influencing parameter of arithmetic mean surface height (Sa) and valley fluid retention index (Svi).

Keywords:Die-mould manufacturing; high-speed milling; 3D surface roughness; ANOVA; analysis of variance

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1. Introduction

The machining methods currently used worldwide for die-cast manufacturing are only optional, or do not offer optimal efficiency, to achieve the highest standards in manufactured die moulds. To reach such standards, engineers must think about new manufacturing techniques, to increase quality and save machining time.

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HSM or high-speed milling technology is relatively new. In order to better define this methodology, it is necessary to use parameters that characterize the surface quality and roughness. However, publicly available scientific publications are not providing in-depth studies on the correlation between HSM and surface topography.[2] These parameters are identified by means of 3D surface roughness measurements, in accordance with the standard ISO 25178:2012 - Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 2: Terms, definitions and surface texture parameters. This methodology is also the new standard for surface texture measurements.

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Our research was begun in Riga Technical University, in cooperation with the Polytechnic University of Valencia, Spain. During this research we needed to explore the surface roughness quality obtained by processing with high-speed milling, using different combinations of cutting regimes. The first part of this research was started in Valencia, where all the subsamples were machined using different combinations of regimes and milling trajectories. For the present purposes, trajectory means tool movement over the material surface.

The aim of this research is to identify what kind of conventional machining methods are currently used for die-mould manufacturing, and if they can be replaced by high-speed machining, as well as the impact of the machining regimes on 3D surface roughness parameters. To achieve this, the following tasks had to be carried out:

a) Comparison of conventional die mould manufacturing techniques and high-speed milling techniques.
b) Take measurements of the 3D surface texture and roughness for the two most frequently used die mould manufacturing steels.
c) Identification of the most characteristic 3D surface texture and roughness parameters after HSM.
d) Mathematical identification of the most critical technological parameters influencing each specific 3D surface roughness parameter.
e) Development of practical recommendations for die mould manufacturers, to apply these technological parameters in the manufacturing process and optimize surface roughness, save machining time and decrease labour costs.

2. High-speed machining: a review

High-speed machining (HSM) has gained importance over the past few years, following technological developments that have enabled its implementation. As a result of advances in machine tools and cutting tool technology, HSM has become a cost-effective manufacturing process for producing parts with high precision and surface quality. Until recently, high-speed machining was applied in machining aluminium alloys for manufacturing complicated parts used in the aircraft industry. This technology was successfully applied with significant improvements in machine tools, spindles and controllers [3, 4]. Recently, with the advance of cutting tool technologies, HSM has also been employed for machining alloy steels for making dies/moulds used in the production of a wide range of automotive components, as well as plastic moulding parts [5]. High-speed machining can be defined as machining at considerably higher cutting speeds and feed rates compared to those in traditional methods. HSM processes enable high material removal rates, low cutting forces, reduced lead times and improved part precision [6]. The distinction between conventional and high-speed machining is based on the workpiece material being machined, type of cutting operation, and the cutting tool used [7]. The high rotation speeds and feed rates of HSM impose new constraints on the tool path: a sharp corner requires the tool to slow down, change its direction and accelerate again until the desired maximum speed is reached again. Also, when cutting hard material, rapid changes in tool load may result in increased tool wear. Since sharp corners or, more generally, points of high curvature of the tool path often also result in a rapid change in the tool load, it is obvious that they should be avoided for HSM tool paths. [11]

Many advantages of HSM have been cited. The most common advantages reported are high metal removal rates, low cutting forces, minimal workpiece distortion, the ability to machine thin-walled sections, use of simple fixtures, little or no damage to workpiece surface integrity, reduction in cutting tool variety, burr-free components, and easier chip disposal [3], [7]. Figure 4 shows some characteristics of the high-speed machining process [8]. Figure 1. also shows that by increasing cutting speeds, the cutting forces can be reduced and better surfaces can be obtained, instead of reduced cutting tool life.

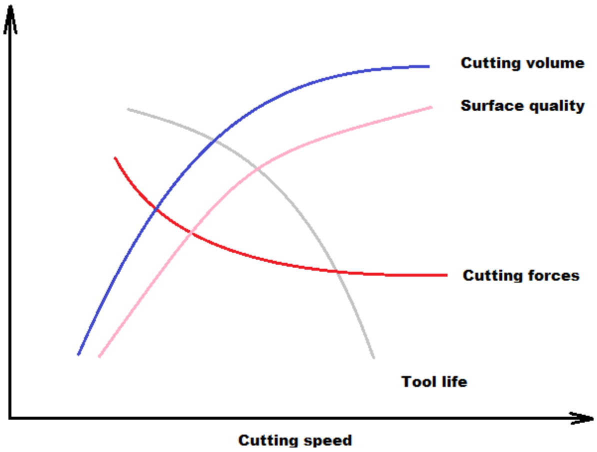


Fig. 1. Characteristics of the high-speed machining process [5].

For the practical aspect of our research, we used a Gentiger GT-66V-T16B high-speed milling machine, with a spindle speed of up to 16,000 min^{-1}, spindle power of up to 26 kW, a rapid feed rate of 30 m/min and maximum working feed rate of 20 m/min. The machine is equipped with a Siemens 840D NC controller and BT-40 cone-type spindle.

3. 3D Surface roughness measurements

The existing standards for surface roughness cover two-dimensional surface roughness parameters (ISO 4287:1984), and also three-dimensional (3D) surface texture, as in real life. The 3D surface roughness parameters in particular are important for solving mechanical contact surface problems related to the accuracy of 3D surface roughness characteristics. [9] In this case, it is necessary to extend this research to surface roughness measurements that give more comprehensive information on surface roughness and texture. To analyse surface texture in this research, the ISO 25178:2012 - Geometrical product specifications - standard was chosen. Measuring the 3D surface roughness requires collecting a precise number of points (in this case, profiles or lines parallel to the main axes of the sample). The surface displacement occurs in two orthogonal directions: x and y (Fig. 2). In the x-direction, the data are collected with Nx being the number of datapoints, whereas in the y-direction there are Ny lines (profiles) [10].

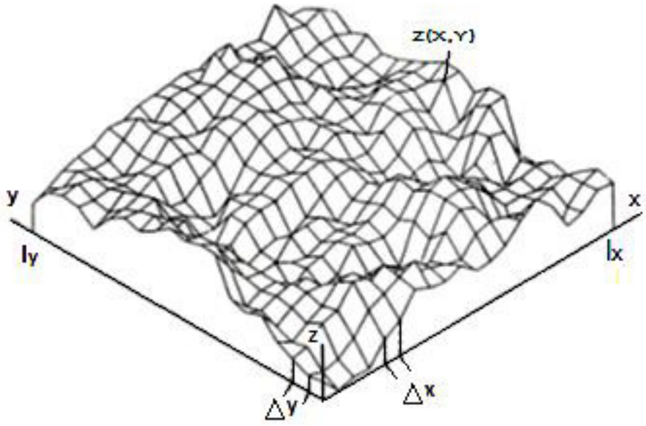


Fig. 2. 3D measurement scheme of surface displacement [7].

The measurements for all machined samples were taken using the Taylor Hobson Form Talysurf Intra 50 measuring device and TalyMap Expert data software was used for the data processing.

4. Approach and research objectives

This research began in the Department of Mechanical and Materials Engineering at the Polytechnic University of Valencia and incorporates work at the Material Processing Technology Department of Riga Technical University. The experiment was based on processing 3 different types of high-strength material with HSM technology, using different combinations of cutting parameters. Two types of processed steels that are widely used in die mould manufacturing 1.2312 (40CrMnMo58-6) (Fig. 3.) and 1.1730 (C45W) were selected. For comparison, a third high-strength material, unalloyed titanium BT1-0 Grade 2, was also chosen.

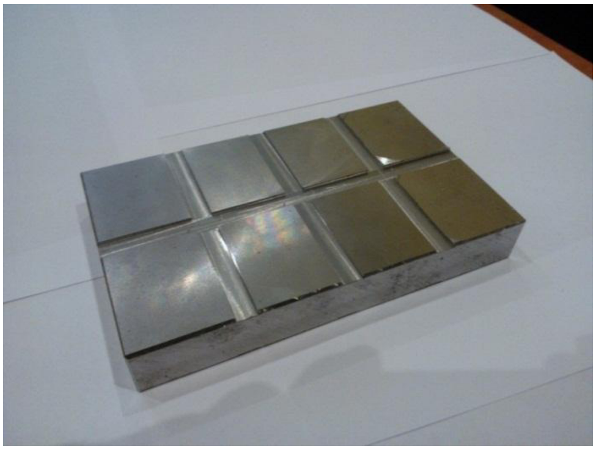


Fig. 3. Material 1.2312 sample with subsamples.

A variable combination of cutting parameters was chosen for each machined sample. Certain parameters were kept constant, such as cutting depth (0.3mm for all samples) and spindle speed (15,707rpm for mould steels and 3,666rpm for titanium). Other chosen parameter values were variable. One of the most potentially significant factors is feed rate. Feed rates were chosen in accordance with manufacturers' recommendations. For mould materials, where spindle speeds are higher, the cutting speeds also are higher. The following feed speeds were chosen for mould steels:

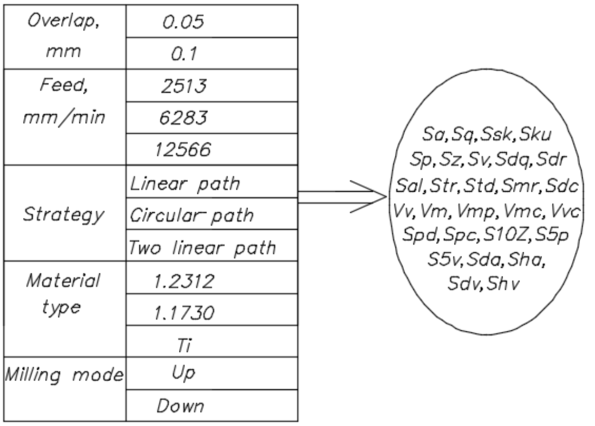
- 2,513mm/min (0.08mm/tooth);
- 6,283mm/min (0.2mm/tooth);
- 12,566mm/min (0.4mm/tooth).

Another of the selected variable technological parameters was tool overlap. Overlap characterizes tool displacement compared with the previous movement trajectory over the material surface. Two different values were chosen: 0.05mm and 0.1mm.

For the cutting strategy, three different cutting strategies were chosen, to approximate experiment to real manufacturing process:

- Linear strategy type or linear path (LP) – linear tool movement over the surface;
- Circular strategy type or circular path (CP) – circular tool movement by Archimedes spiral;
- Two linear strategies or two linear paths (TLP) – the combination of linear tool movement along both the X and Y axes.

Both types of milling modes were used – up (cutter rotation coincides with feed direction) and down (cutter rotation is opposite to the feed direction) milling modes. In this research, we need to analyze the impact of all the aforementioned parameters on the 3D surface texture parameters (Fig.4.)



Overlap, mm	0.05
	0.1
Feed, mm/min	2513
	6283
	12566
Strategy	Linear path
	Circular path
	Two linear path
Material type	1.2312
	1.1730
	Ti
Milling mode	Up
	Down

Fig. 4. Input parameter influence on 3D surface texture parameters.

Each machined sample is divided into 16 subsamples, processed by different combinations of technological parameters. When all subsamples were machined, the surface texture measurements (3D roughness measurements) were taken. Also photographs were taken to compare with pictures from the roughness measuring device Talymap Expert software.

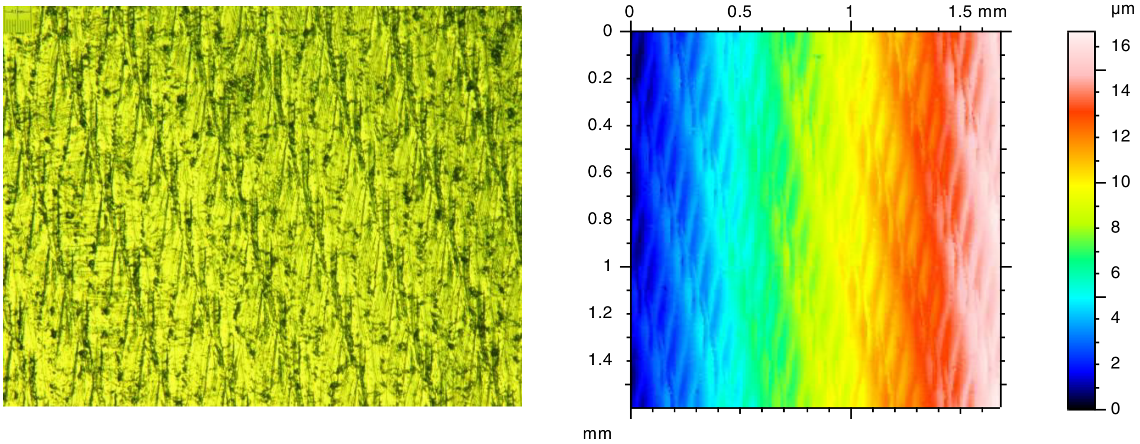


Fig. 5.a) Sample no. 6. (LP 0.05, Feed 0.4mm^{-1}) microscope camera image b) Surface texture of sample. 6. (LP 0.05, Feed 0.4mm^{-1}) by Talymap Expert.

5. Analysis

After all the measurements were taken, the data was divided into the appropriate groups and the most significant 3D roughness parameters for high-speed milling were chosen. This was done by preparing the correlation matrix in the Rcommander software, where a set of 3D roughness parameters are inserted into the matrix of n random variables, to obtain the most significant parameters for each group.

The chosen 3D roughness parameters were collated in charts, to prepare graphs that illustrate changes in roughness parameters resulting from feed level, overlap and strategy type. In order to describe the influence of one input parameter on surface roughness parameters, multifactorial analysis is required, which characterizes the impact of several input parameters on specific surface roughness parameters.

For the ANOVA multifactorial analysis using Rcommander software, all technological parameters have to be replaced with factors. ANOVA – analysis of variance is then conducted on pairs of these factors, using each chosen surface parameters as a response function, to see how each specific factor influences one or another surface texture parameter.

The trend line coefficients of the polynomial regression equation with argument x for material 1.1730 (sample no.6. with linear pattern) shows that the feed rate is the major influence (Fig.6). This is approved also by ANOVA multifactorial analysis, done by Rcommander software and SPSS Statistics.

$$y = -31.818x^2 + 14.568x - 0.4076 \tag{1}$$

However, for the sample with circular pattern milling, the equation ratios confirm that differences between feed levels is lower (Fig.7):

$$y = -13.84x^2 + 6.29x - 0.01 \tag{2}$$

In a sample machined with an overlap of 0.1mm, the roughness parameter Sa increases together with feed level. The equation ratios prove this correlation:

$$y = -8.14x^2 + 6.27x - 0.13 \tag{3}$$

In those graphs, it shown, that behavior of regression trend-line is similar in both of cases for parameter Sa. The situation is not so definitely clear for other texture parameters. For example, parameters Sku and Stp are strongly influenced by chosen material type. Texture parameters in average is 1,2 times lower for material with higher mechanical properties, and lower elongation. Feed rate impact than is only secondary, influencing parameter Stp only at low overlap rates. Therefor parameter Str - Texture aspect ratio of the surface, is mostly affected by feed level. Ratio shows, that after feed level changes, the balance of processing is missed and forces, probably, should be different in cutting process.

When this analysis is carried out for each of the three selected materials, it becomes clear that the technological parameters of feed rate, strategy and milling mode are more pronounced – there is a non-linear correlation between surface roughness parameters and the technological parameters. Therefore, a technological parameter such as overlap can be excluded from further analysis.

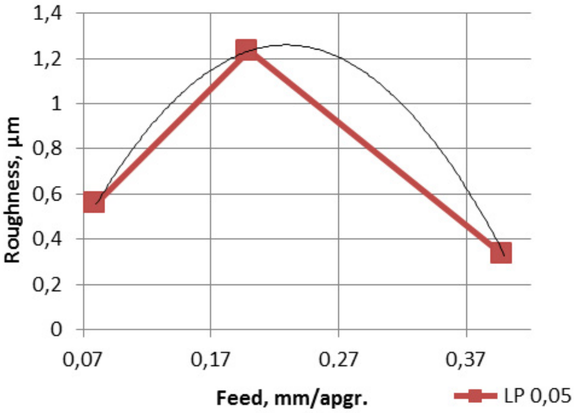


Fig. 6. Sa Parameter’s dependence on feed level with linear strategy for material type 1.1730.

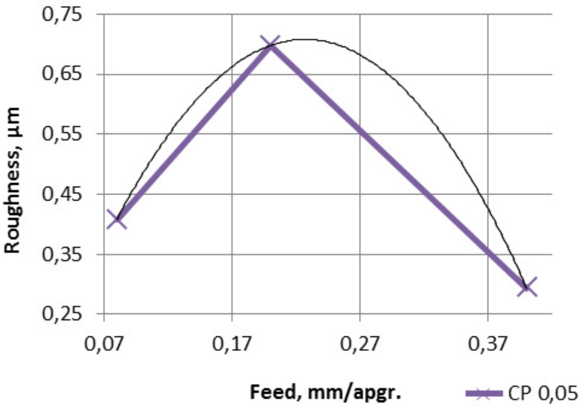


Fig. 7. Sa Parameter’s dependence on feed level with circular strategy for material type 1.1730.

After analysis, we identified which technological parameter affects each particular surface roughness parameter. These are given in Table. 1. To mention appropriate values of texture parameters for each of technological regimes, this research should be continued, based on those conclusions provided by this paper. In comparison with other researches, this paper provides actual data about influence significance of chosen technological regimes.

Table 1. Technological parameters and Surface texture parameters influenced by them.

3D texture parameter	Influenced by	ANOVA signif. ratio
Sa	Strategy	0.002253
Sku	Material	0.01678
Stp	Material	0.03999
Str	Feed rate	0.01621
Svi	Strategy	0.04633

Conclusions

By using modern surface machining methods in tool manufacturing industry, like in die mold manufacturing, is just as much as need to use modern surface characterization methods, such of 3D surface roughness measurements. If there are clearly defined technological parameters and obtained surface roughness parameters, of conventional tool manufacturing, than there is need to define surface texture parameter dependence of used technological regimes. The following results have been introduction of this research. Results are based on mathematically proven hypotheses, to show the dependence of surface texture parameters on technological parameters.

Analysis of available literature indicates that HSM technology can fully replace conventional machining methods, such as milling, grinding, electromechanical and electro-erosion methods. Analyses show that HSM technology is being used increasingly nowadays, to save machining time and reduce manufacturing costs.

1. Based on the correlation matrix, the five most characteristic surface texture parameters for HSM were chosen. They are Sa – the arithmetical mean height of the surface, Sku – the kurtosis of the scale limited surface, STp – the height of the bearing area ratio curve, Str – the texture aspect ratio and Svi – the valley fluid retention index.
2. ANOVA multifactorial analysis was conducted for the five most characteristic surface texture parameters, in which the most significant influences were identified as machining strategy and material type.
3. Data analysis identifies that the circular machining strategy generally gives better results: 1.5 to 2 times lower average surface roughness than the linear machining strategy.
4. Our research indicates that the most significant influence is the material's mechanical properties. This is supported by the use of various technological parameters, which resulted in different surface roughness parameter values and their distribution, and proven by ANOVA analysis.
5. The material's mechanical properties have the greatest influence on surface roughness parameters. These are identified in the parameters Sku and Stp. The Stp parameter is affected by changes in the material's mechanical properties. When cutting forces are altered, increased vibrations result from surface defects that occur in the form of surface roughness peaks, which are distributed irregularly over the surface. These peaks can be up to 5 times higher than the rest of the measured surface. The most significant result was seen in samples where the parameter St > 8μm.

Evaluating the overall factor influence on surface texture parameters and based on the conclusions above, some practical recommendations can be made for applying technological parameters in the manufacturing process when using HSM technology.

1. In the case of one type of material, the greatest influence is the type of manufacturing strategy:
    a) It is recommended to use a circular path, as proved by roughness parameters and surface micro-topography image, where the surface has the lowest roughness and the most even structure.
    b) Conversely it is recommended to use a linear path where the overall surface roughness parameters are lower than with the circular path.
    c) It is advisable to avoid using Two Linear paths. In the second passage, the material is not in fact being cut. In this case, the surface texture peaks are smoothed by the cutting edge.
2. It is important to observe the material's mechanical properties.
    a) Material 1.1730 is more reliable for die mould manufacturing when using HSM technology, compared with the other materials used in this research.
    b) For unalloyed titanium machining, we recommend not using the same technological parameters as for die mould material machining, otherwise surface roughness will be significantly increased.
3. The third most significant technological factor is feed rate.
    a) We would recommend using a low or exceptionally a medium feed rate, when it is necessary to speed up production.
    b) The average feed rate is recommended for machining unalloyed titanium.

In the next stage, it's to increase amount of machined samples, to make measurements of already machined sample with different mechanical properties (Sample Nr.4.). Authors predict that this will increase the probability of getting more precisely correlation between cutting technological parameters and surface roughness parameters, including surface micro-hardness.

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