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SURFACE ROUGHNESS AND ITS PREDICTION IN HIGH SPEED MILLING OF ALUMINUM ALLOYS WITH PCD AND CEMENTED CARBIDE TOOLS

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Abstract
Milling structural components from aluminum under enormous requirements of productivity and quality from the aerospace perspective is still the subject of extensive research.
The assessment strategies of the surface quality are a big challenge for the surface measurement technique, since only a fraction of the manifesting surface topography can be described with the help of two-dimensional measured variables. The aim of this experimental investigation is a description of several influences on the parameter of the surface roughness Ra and to analyze the prediction of these values.
As a result, it can be shown that a more in-depth analysis is necessary to describe the surface quality and topography, which goes beyond the simple specification of roughness parameters.

Keywords:
High speed machining, aluminum, PCD, milling, surface quality, quality prediction

1 INTRODUCTION

Machining integral components from aluminum is a fundamental prerequisite for components in mechanical engineering, plant construction and also for filigree high-tech aerospace structures [Teicher 2019]. It is of important to note that machinability of aluminum alloys varies significantly and that knowledge of machining properties with a focus on the resulting surface topography and roughness is essential [Santos 2016]

The prediction of the resulting surface topography and the derivation of parameters which are relevant for the process are of great economic importance [Benardos 2003]. For milling, the particular challenge is to determine the micro-geometry of the cutting edges of a multi-tooth tool and to include concentricity errors into the calculation [Felhö 2018].

If these parameters are known, an intersection model o between the multi-tooth tool and the workpiece is possible, so that a very good prediction of the roughness parameters can be achieved [Felhö 2015, Wang 2019].

A problem for calculations of tool-workpiece intersection is that special effects due to wear caused by build-up cutting edge formation, abrasion and cutting edge chipping can be insufficiently taken into account. Hence, these effects result in unpredictable surface structures of insufficient quality. Artificial neural networks [Kechagias 2015] are then suitable for the prognosis of roughness parameters like Ra, Rsm and Rt.

Various methods exist to solve these challenges. On the tool side, there are investigations that examine the influence of the contact substrate with aluminum. Relevant contact substrates are coated and uncoated hard metals as well as polycrystalline diamond (PCD). It can be shown that an influence of this configuration changes the cutting and wear behavior. PCD followed by thick-film chemical vapor deposition (CVD) diamond tools are considered to be the most favorable variant with regard to tool life [Vandelvelde 1999] and built-up edge formation [Guntreddi 2017, Gomez-Parra 2013]. This relationship is particularly valid for dry machining, where the advantages of diamond coated tools have a high cost potential [Lahres 1997a]. Further coatings with "soft" morphological regions show advantageous properties for high-strength alloys as well as for cast alloys in the application with no cooling lubricant [Lahres 1997b].

On the tool side, further developments are being made to manipulate the PCD cutting edge shape in order to improve chip breaking in aluminum alloy 6082 [Polzer 2019]. However, despite the advantages of PCD, this procedure is in many cases time-consuming and cost-intensive, so that efforts are focused on low-cost finishing processes by EDM [Trcka 2018a, Trcka 2018b].

In parallel, technological optimizations are necessary to exploit the potential of tool developments. This includes the controlled injection of a cooling lubricant as MQL [Lopez de Lacalle 2002] or in the form of liquid nitrogen [Jebaraj 2019]. The cutting speed and the tooth feed rate are identified as most important parameters influencing the surface roughness [Subramanian 2014].

Simulation techniques are another way of analyzing and optimizing the machining behavior of aluminum alloys. In addition to the assessment of chip formation and built-up edge formation [Haddag 2016] as well as burr formation [Bourlet 2016], the machining forces and the mechanical loads are always in the focus of analysis. Simulation techniques based on finite element simulation can be used to assess effects in the application of high cutting speeds of up to 2000 m/min which describe the thermal behavior in detail. It can be shown that PCD as a cutting material is basically cheaper than carbide, as the thermal loads on the tool cutting edge do not reach critical values for PCD [Davim 2008].

This raises the given research question: Which variables have a significant influence on the surface topography and roughness parameters and what dependence is given to the cutting conditions, the material and the tool? On the basis of experimental investigations, the influence of the mentioned parameters on the roughness parameter Ra is investigated and the form of deviations from predicted values.

2 EXPERIMENTAL CONDITIONS

The experimental investigations were carried out on a Mikromat 4V HSC high-speed machining center as face milling operation for slot milling *Fig. 1*. The machine data can be found in *Tab. 1*.

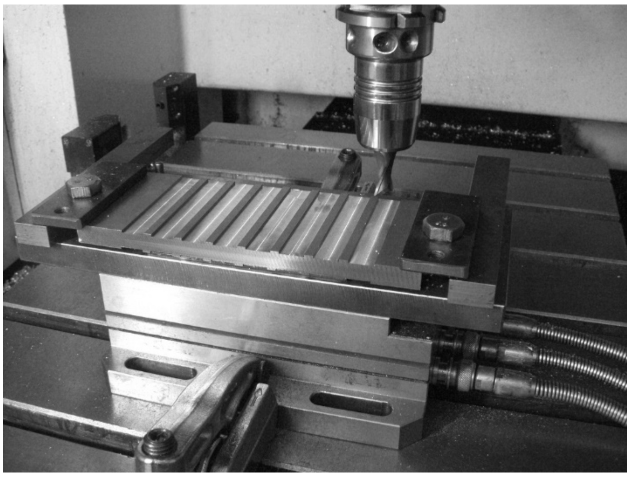


Fig. 1: Experimental set-up for slot milling.

Tab. 1: Parameters of the Mikromat 4V machining center.

Parameter	**Unit**	**Value**
Feed rate v_f	m/min	0 ... 30
Power Main spindle (100 %ED) P	kW	16
Spindle speed n	min^{-1}	0 ... 30000
Size working table	mm	400 x 500

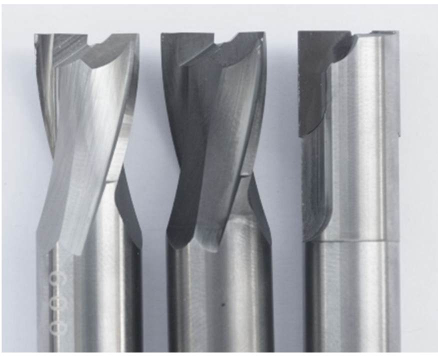


Fig. 2: Milling tools used for the experiments (left – uncoated UC; middle – CVD diamond coated DIA; right – PCD tool).

The tools were coupled in a hydraulic expansion chuck with a HSK50 tool holder. During the tests, a cooling lubricant was not used and only compressed air was injected to remove the chips.

Tab. 2: Parameters of the milling tools.

Parameter	**Tool**		
	UC	DIA	PCD
Basis tool substrate	Cemented tungsten carbide EMT 100	Cemented tungsten carbide EMT 100	Poly-crystalline diamond
Coating	-	CVD – diamond	-
Shank substrate	as tool substrate	as tool substrate	Cemented Tungsten carbide EMT 100
Tool diameter d / mm	12	12	12
Number of teeth z	2	2	2
Tool cutting edge in-clination λ_s / °	15	15	0
Tool side rake γ_f / °	10	10	0

Three different tool variants were investigated, which are shown in *Fig. 2* described in detail in The tools were coupled in a hydraulic expansion chuck with a HSK50 tool holder. During the tests, a cooling lubricant was not used and only compressed air was injected to remove the chips.

The tool with the abbreviation DIA is geometrically identical with the uncoated tool UC and only with a nanocrystalline CVD diamond layer (layer thickness 6-15 µm, hardness 10000 HV10). The tungsten carbide tools are made of the substrate EMT 100 (WC 93 %, Co 6 %, other carbides 1 %) of the manufacturer Extramet AG, which is characterized by the properties shown in *Tab. 3* and is especially designed for diamond coating.

On the workpiece materials side, the focus was laid on two technically highly relevant aluminum alloys 5754 and 6082 which are chemically characterized in *Tab. 4* and mechanically in *Tab. 5*.

Tab. 3: Properties of the used cemented tungsten carbide.

Parameter	**Unit**	**Value**
Mass density ρ	g/cm³	14.8 ± 0.1
Hardness ISO 3878	HV 30	1740...1860
Transverse rupture strength	N/mm²	3900±100
Average grain size	µm	≈0.8

Tab. 4: Chemical composition of the aluminum alloys.

Element	**Weight %**	
	5754-H111	**6082-T6**
Si	0.4	0.7 – 1.3
Fe	0.4	0.5
Cu	0.1	0.1
Mn	0.5	0.4
Mg	2.6 – 3.6	0.6 – 1.2
Cr	0.3	0.25
Zn	0.2	0.2
Ti	0.15	0.1
Al	Balance	

The aluminum alloys were used as rolled plates. The slots were milled parallel to each other on the respective plates (*Fig. 1*). After cleaning, the sample plates were measured on a Hommel-Etamic T8000 roughness measuring instrument according to ISO 4288 with lt= 4.8 mm and lc= 0.8 mm for the arithmetic mean values. The measuring direction was identical with the feed direction of the tool.

Tab. 5: Mechanical properties of the aluminum alloys.

Parameter and Unit	Value	
	5754-H111	6082-T6
Ultimate Tensile Strength R_m /MPa	190 - 240	300
Yield Strength R_{p02} /MPa	80	255
Elongation at break A /%	18	9

3 EXPERIMENTAL RESULTS AND DISCUSSION

The primary focus was on the analysis of the influence of the tools and the technological parameters on the roughness parameters. This means that relevant roughness parameters have to be evaluated with regard to their relation to the

- feed per tooth f_z,
- cutting speed v_c,
- material and
- tool substrate and coating.

The arithmetic mean roughness value Ra represents the main evaluation characteristic parameter. Basically, it is shown that there is a directly proportional relationship between the set tooth feed rate and the roughness parameter Ra. This relationship has already been laid down according to Equation 1 in the literature [Wang 2004]:

$$Ra = \frac{f_z}{4 \cdot \cot \kappa'_r} \quad (1)$$

It is remarkable that the corresponding parameter Ra only depends on the technological value of the feed rate and the tool parameter of the tool minor cutting edge angle κ‘r. This means that the underlying relationship is de facto a calculation of an intersection that ignores technological and material aspects.

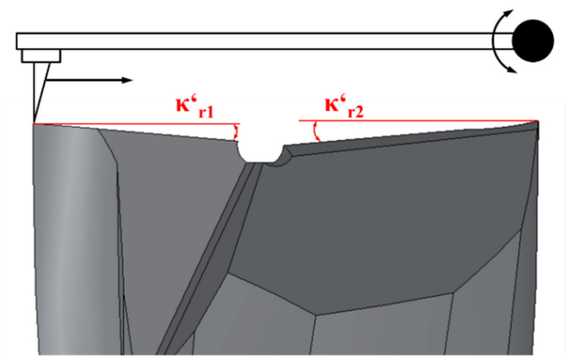


Fig. 3: Schematic illustration of the measurement of the face cutting edge contour to determine the tooth related tool minor cutting edge angle κ‘r.

Within the scope of the investigations, the individual values of the tool minor cutting edge angle were determined. The basis for this is a contour measuring unit of the Hommel-Etamic T8000 stylus measuring device. With the help of a newly developed measuring blade, the face cutting edge contour was measured to determine the tool minor cutting edge angle (*Fig. 3*).

This result is also used to carry out calculations of intersections on the basis of measured tool data with the aid of the data record generated by the measuring process and thus to ensure the prediction of the surface topography.

In principle, the smaller angle should be selected for the measurement of the tool minor cutting edge angle for the calculations and the prediction of the roughness parameters, since this angle has a topography-generating effect for the development as kinematic roughness. On the basis of this measuring task, the relevant angles and the predicted roughness values according to Equation 1 could be calculated for the considered tools (*Tab. 6*).

Tab. 6: Calculated Ra values as a function of the tool and the feed per tooth.

Feed per tooth f_z /mm	Roughness Ra /µm		
	UC (κ’r= 4.34°)	DIA (κ’r= 2.27°)	PCD (κ’r= 0.27°)
0.025	0.47	0.25	0.03
0.075	1.47	0.74	0.09
0.15	2.85	1.49	0.18
0.25	4.74	2.48	0.29

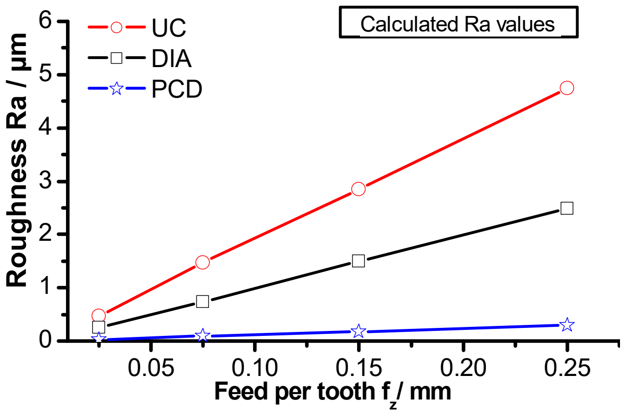


Fig. 4: Calculated Ra values according to Tab. 6.

For the Ra values from the experiments, a linear behavior can be proven in principle (see *Fig. 5* - *Fig. 10* except *Fig. 8*).

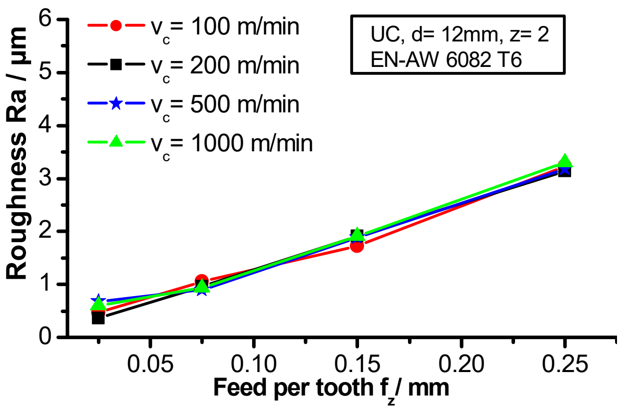


Fig. 5: Ra values of the uncoated tool for aluminum 6082 as a function of the cutting speed and the feed per tooth.

This relationship is also described by equation 1 in the direct proportionality between the feed per tooth feed and the roughness parameter Ra. This correlation and the proof based on the investigations carried out represent a good initial assumption for the prediction. Nevertheless, there are deviations from this correlation. This is particularly evident in the limit ranges of high and low cutting speeds and feed per tooth. There are various reasons for this.

On the one hand ploughing and rubbing effects occur in the area of low tooth feeds due to the defined cutting edge radius if the value falls below a critical value, which according to [Liu 2006] is described as the quotient of the minimum chip thickness and the cutting edge radius as normalized minimum chip thickness λ_n and which, for example, is approx. 0.4 for the aluminum alloy EN-AW 6082 T6 and is independent of the cutting speed for the area investigated. This means that the cutting edge radius of the tools for the tooth feed of 0.025 mm, which is equivalent to the minimum chip thickness, must be at least 62.5 µm in order to be outside the critical range.

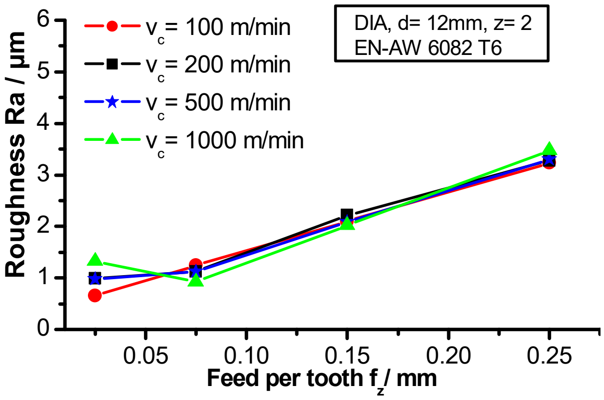


Fig. 6: Ra values of the diamond coated tool for aluminum 6082 as a function of the cutting speed and the feed per tooth.

This issue can be interpreted as a reason for the behavior that higher roughness values tend to be produced when tools with diamond coating are used, since the cutting edge radius is increased by the coating in general and with thick film CVD diamond coatings in particular. This effect is detectable for both the 6082 and the 5754 aluminum alloy.

A further aspect, which generally has a negligible influence on the tool side, however, explains the effects of increasing roughness values at simultaneously increasing cutting speed according to *Fig. 6*, refers to the concentricity quality of the tool.

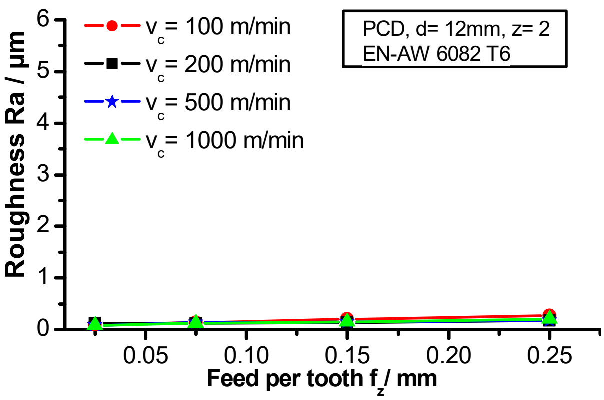


Fig. 7: Ra values of the PCD tool for aluminum 6082 as a function of the cutting speed and the feed per tooth.

In principle, tools are designed rotationally symmetrically in order to minimize loads on the tool, clamping devices and bearings. However, this is technically limited, so that in the case of manufacturing flaws, minimal tumbling movements of the tool occur and stronger cutting grooves form on the surface with increasing cutting speed. These are ultimately measurable as increased roughness.

A much more important effect, however, is given by the choice of cutting speed in conjunction with the material. Especially with the application of low cutting speeds with ductile aluminum alloys of the series 1XXX, 5XXX or, apart from machining alloys with additives of lead, with aluminum alloys with fundamentally low strength, built-up cutting edges and surface smearing occur on the tool.

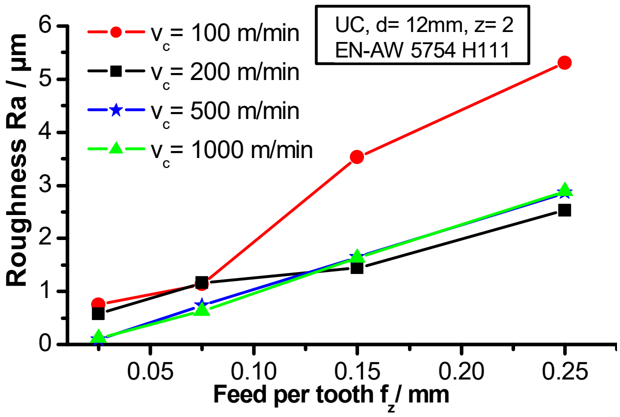
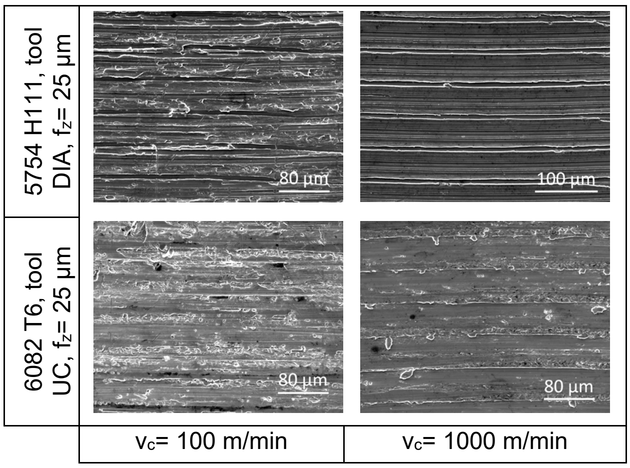


Fig. 8: Ra values of the uncoated tool for aluminum 5754 as a function of the cutting speed and the feed per tooth.

This effect increases with decreasing cutting speeds, as shown in *Fig. 8*. The conclusion that can therefore be drawn in comparison to the results of tools coated as PCD or with a diamond coating is that both the coefficient of friction and the adhesion tendency of aluminum to diamond are lower compared to hard metal [Rao 2001]. These results are in line with the findings obtained in milling tests with PCD tools on aluminum alloy 7075 [Kim 1997]. The influence of the cutting speed, which is expressed in the roughness parameter Ra, can also be clearly shown in the analysis of the surface shape.

As the cutting speed increases, the effects of smearing and tearing are reduced, as shown in *Tab. 7*.

Tab. 7: Surface topography of milled aluminum as a function of the alloy and the cutting speed (SEM 200x).



It should be noted here that a distinction must be made between surface shape and surface properties, which are used, for example, as roughness properties Ra. This means, for example, that smearing can break through the typical groove shape during milling, fill profile valleys with material and therefore reduce the roughness values.

On the one hand, this explains why lower Ra values can be measured for the material 5754 compared to the higher-strength aluminum 6082. On the other hand, it can also be justified that the predicted values according to *Tab. 6* are higher than the measured values for both alloy 5754 and 6082.

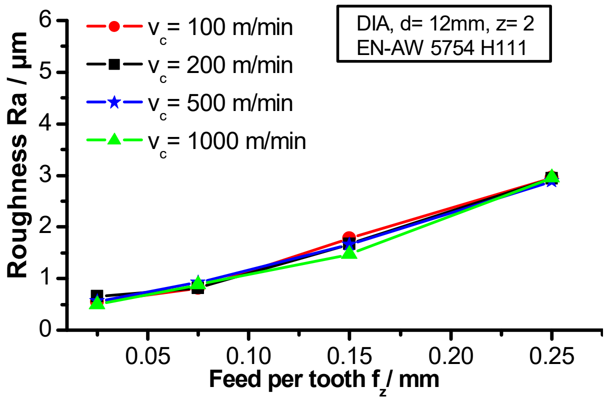


Fig. 9: Ra values of the diamond coated tool for aluminum 5754 as a function of the cutting speed and the feed per tooth.

It is noteworthy that the results of the PCD tool are independent of the cutting speed and the material (see *Fig. 7* and *Fig. 10*). This is important because, unlike cemented tungsten carbide-based tools, these tools are not geometrically optimized. This means that the base of a PCD blank was used to set the tool orthogonal clearance angle. Due to the flat semi-finished product in the form of a PCD blank, geometric optimizations and the integration of free-form surfaces are only possible to a limited extent, so that, for example, complex techniques for the integration of microstructures must be selected [Polzer 2019].

However, the performance of the tools is given, as the very good results from the roughness parameters show, so that it can be concluded that the cause lies in the specific tribological properties of PCD. Further investigations are necessary.

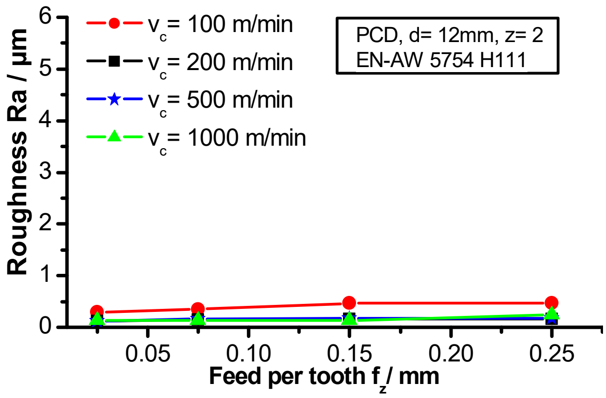


Fig. 10: Ra values of the PCD tool for aluminum 5754 as a function of the cutting speed and the feed per tooth.

4 SUMMARY AND CONCLUSION

Experimental investigations during the milling of aluminum alloys with different cutting material substrates have shown that roughness parameters can be predicted. The basis is the geometric measurement of the face cutting edges with the tool minor cutting edge angle. However, there are limits here which are given by the machinability of the respective alloy. These limits refer to results obtained with tooth feed settings in which very small values in the order of the cutting edge radius are not predictable. Furthermore, the characteristic values increasingly differ with decreasing cutting speed. These findings relate above all to tools with the core substrate hard metal. Tools with PCD substrate show very good results for all process combinations, the reason being the better tribological properties of PCD in combination with aluminum. Here, however, further investigations are required to investigate detailed interactions, for example to establish favorable diamond coatings.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[Benardos 2003] BENARDOS, P.G., VOSNIAKOS, G.C. 2003. Predicting surface roughness in machining: A review. International Journal of Machine Tools and Manufacture 43, 8, 833–844.

[Bourlet 2016] BOURLET, C., FROMENTIN, G., HARIKA, E., AND CROLET, A. 2016. Analysis and Modeling of Burr Formation During the Plane Milling of Cast Aluminum Alloy Using Polycrystalline Diamond Tools. Journal of Manufacturing Science and Engineering 138, 8, 081010.

[Davim 2008] DAVIM, J.P., MARANHÃO, C., JACKSON, M.J., CABRAL, G., AND GRACIO, J. 2008. FEM analysis in high speed machining of aluminium alloy (Al7075-0) using polycrystalline diamond (PCD) and cemented carbide (K10) cutting tools. International Journal of Advanced Manufacturing Technology 39, 11–12, 1093–1100.

[Felhö 2015] FELHO, C., KARPUSCHEWSKI, B., AND KUNDRAK, J. 2015. Surface roughness modelling in face milling. Procedia CIRP 31, 136–141.

[Felhö 2018] FELHÖ, C. AND KUNDRAK, J. 2018. Effects of Setting Errors (Insert Run-Outs) on Surface Roughness in Face Milling When Using Circular Inserts. Machines 6, 2, 14.

[Gomez-Parra 2016] GOMEZ-PARRA, A., ÁLVAREZ-ALCON, M., SALGUERO, J., BATISTA, M., AND MARCOS, M. 2013. Analysis of the evolution of the Built-Up Edge and Built-Up Layer formation mechanisms in the dry turning of aeronautical aluminium alloys. Wear 302, 1–2, 1209–1218.

[Guntreddi 2017] GUNTREDDI, B., PAUL, S., AND GHOSH, A. 2017. Performance of Vacuum Brazed PCD Tools during Turning of Al-7075 under SQCL- Environment Performance of Vacuum Brazed PCD Tools during Turning. Proceedings of 6th International & 27th All India Manufacturing Technology, Design and Research Conference (AIMTDR-2016) December 2016, 1248–1253.

[Haddag 2016] HADDAG, B., ATLATI, S., NOUARI, M., AND MOUFKI, A. 2016. Dry Machining Aeronautical Aluminum Alloy AA2024-T351: Analysis of Cutting Forces, Chip Segmentation and Built-Up Edge Formation. Metals 6, 9, 197.

[Jebaraj 2019] JEBARAJ, M., PRADEEP KUMAR, M., YUVARAJ, N., AND MUJIBAR RAHMAN, G. 2019. Experimental study of the influence of the process parameters in the milling of Al6082-T6 alloy. Materials and Manufacturing Processes 6914.

[Kechagias 2015] KECHAGIAS, J., KYRATSIS, P., AND MASTORAKIS, N. 2015. On Prediction of Surface Roughness of Al 7075 alloy during Slot Milling using NN Modeling. Recent Advances on Mechanics, Materials, Mechanical Engineering and Chemical Engineering On April, 98–107.

[Kim 1997] KIM, J.-D. AND KANG, Y.-H. 1997. High-speed machining of aluminium using diamond endmills. International Journal of Machine Tools and Manufacture 37, 8, 1155–1165.

[Lahres 1997a] LAHRES, M. AND JÖRGENSEN, G. 1997. Properties and dry cutting performance of diamond-coated tools. Surface and Coatings Technology 96, 2–3, 198–204.

[Lahres 1997b] LAHRES, M., MÜLLER-HUMMEL, P., AND DOERFEL, O. 1997. Applicability of different hard coatings in dry milling aluminium alloys. Surface and Coatings Technology 91, 1–2, 116–121.

[Liu 2006] LIU, X., DEVOR, R.E., AND KAPOOR, S.G. 2006. An Analytical Model for the Prediction of Minimum Chip Thickness in Micromachining. Journal of Manufacturing Science and Engineering 128, 2, 474.

[Lopez de Lacalle 2002] LOPEZ DE LACALLE, L.N., LAMIKIZ, A., SANCHEZ, J.A., AND CABANES, I. 2002. Cutting conditions and tool optimization in the high-speed milling of aluminium alloys. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 215, 9, 1257–1269.

[Polzer 2019] POLZER, A., KREHLIK, L., AND TRCKA, T. 2019. END MILLS WITH PCD INSERTS INCLUDING INTEGRAL CHIP BREAKER. MM Science Journal 2019, 01, 2808–2813.

[Rao 2001] RAO, B. AND SHIN, Y.C. 2001. Analysis on high-speed face-milling of 7075-T6 aluminum using carbide and diamond cutters. International Journal of Machine Tools and Manufacture 41, 12, 1763–1781.

[Santos 2016] SANTOS, M.C., MACHADO, A.R., SALES, W.F., BARROZO, M.A.S., AND EZUGWU, E.O. 2016. Machining of aluminum alloys: a review. International Journal of Advanced Manufacturing Technology 86, 9–12, 3067–3080.

[Subramanian 2014] SUBRAMANIAN, M., SAKTHIVEL, M., AND SUDHAKARAN, R. 2014. Modeling and Analysis of Surface Roughness of AL7075-T6 in End Milling Process Using Response Surface Methodology. Arabian Journal for Science and Engineering 39, 10, 7299–7313.

[Teicher 2019] TEICHER, U., PIRL, S., NESTLER, A., HELLMICH, A., IHLENFELDT, S. 2019. A novel hybrid clamping system for sheet metals and thin walled structures. Procedia Manufacturing, accepted manuscript

[Trcka 2018a] TRCKA, T., POLZER, A., AND SEDLAK, J. 2018a. Shoulder End Mills With Pcd Inserts Sharpened By Different Electrical Technologies. MM Science Journal 2018, 04, 2536–2542.

[Trcka 2018b] TRCKA, T., POLZER, A., AND SEDLAK, J. 2018b. END MILLS WITH PCD INSERTS SHARPENED BY DIFFERENT ELECTRICAL TECHNOLOGIES. MM Science Journal 2018, 01, 2192–2197.

[Vandevelde 1999] VANDEVELDE, T.C.S., VANDIERENDONCK, K., VAN STAPPEN, M., DU MONG, W., AND PERREMANS, P. 1999. Cutting applications of DLC, hard carbon and diamond films. Surface and Coatings Technology 113, 1–2, 80–85.

[Wang 2004] WANG, M.Y. AND CHANG, H.Y. 2004. Experimental study of surface roughness in slot end milling AL2014-T6. International Journal of Machine Tools and Manufacture 44, 1, 51–57.

[Wang 2019] WANG, R., WANG, B., BARBER, G., GU, J., AND SCHALL, J.D. 2019. Models for Prediction of Surface Roughness in a Face Milling Process Using Triangular Inserts. Lubricants 7, 1, 9.