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Efficient Ceramics Manufacturing through Tool Path and Machining Parameter Optimisation

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There has been an increasing trend in using ceramics in the application areas where high hardness and thermal resistance are necessary, especially in energy production branch where gas turbines are coated with ceramics. The paper introduces experiments and results of ceramics machining using regular cutting tool geometry. Two machining strategies were analysed (wave form and cycloid), the number of critical process parameters were reduced significantly and remarkable tool life extension was reached using the test machine build by the authors.

I. INTRODUCTON

There has been an increasing trend in using ceramics in the application areas where high hardness and thermal resistance are necessary. [1] The energy industry takes part in this trend too. Gas turbines have been used for producing electric energy where the condition of reaching the highest efficiency is the resistance to high temperature. This is the reason why the turbine blades are coated with ceramic. In favour of increasing more the resistance of the blades, besides the ceramic coating, cooling drains have to be prepared in the basic material.

Technically it is advisable to coat the material with ceramics before machining the cooling drains.

Firstly, the ceramics has to be manufactured. There are different technologies to do so, e.g. water sandblasting, laser drilling. [13][14][15]s The weak points of these technologies are the complex technology and the expensive machine time. Nowadays machining with regular geometry (turning, milling) has been one of the most reasonably priced technologies, however because of fast tool wearing, the method can be economically poor if this technology is not optimized for machining that particular ceramic material and task. There are several theoretical and practical open questions in this area, such as whether the milling technology is the best way in ceramic machining. For this reason, a comprehensive experiment plan was created that aims to adapt this technology in the industrial environment.

This article presents the task of ceramic machining method, the elaborated experimental plan, and the results of the performed experiments.

In the next chapter the technological parameters and possible tool paths are summarized with the help of a literature overview that are followed by the explanation of the experimental plan and its manufacturing results. A short outlook for further research is followed by the conclusions and references.

II. LITERATURE OVERVIEW

There are plenty of technological parameters that influence the milling of ceramics. However, the literature shows that the most influencing parameters are the following: [2] [3] [4] [5]

Technological parameters

- axial cutting depth
- radial cutting depth
- cutting speed
- feed
- tool tilt angle

Geometry of cutting tool

- flank angle
- rake angle
- number of teeth

Tool material, coating

- basic tool material
- type of coating
- thickness of coating
- grain size
- number of coating layers

Type of cooling
Other parameters

- combined machining technology

Besides the technological parameters, it is essential to mention the parameters of the base material as well. [16] The most influencing material parameters are the *rigidity* and *hardness* that have to be taken into consideration when machining with regular geometry tools.
One of the most important questions of cutting with regular geometry tool is that how to cut in plastic deformation area instead of in brittle area. K. Ueda and his colleagues cut plenty of ceramics material to find solution for this question, and they found that materials that have high fracture toughness can be cut easier in plastic deformation area with optimal cutting speed and feed.[6] However, with low fracture toughness they did not find a parameter combination that could be cut in the ductile deformation zone.
The other author of the mentioned publication who conducts some research into the ductile-brittle range in machining method is Muhammed A, who tried to find what those cutting parameters were which influence the ductile range.[2] It was found that there was a critic parameter belonging to the cutting depth and feed value which affects the chip-removal mechanism. These results are summarized in Figure 1.

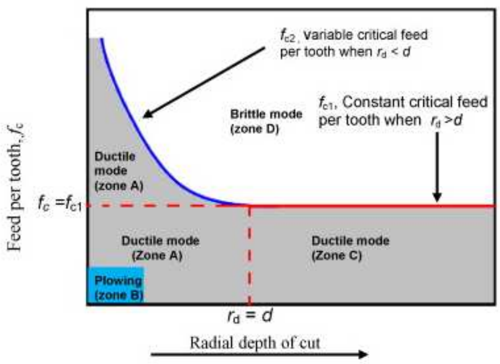

Fig. 1: Critical value of feed-depth to reach the plastic deformation range [2]

During their experiment it was found that there is a critical value of cutting depth and feed where the analyzed material can be manufactured in the ductile removal area. Under a certain cutting depth, the value of feed can be increased without the removal of the cutting mechanism in brittle area. This means that the plastic deformation strongly depends on the value of the cutting depth. Difference should to be made between 2 types of cutting depth, axial cutting depth and radial cutting depth. [2][3][4]
In case of axial cutting depth the tool cuts along the tool axle, while in case of radial cutting depth the tool cuts along tool diameter. These parameters take part in the strength of the cutting tool and in keeping the process in ductile removal area.
The literature gives reference on an oncoming formula which defines the optimal value of cutting depth, which is the following: [4]:

$$d_{crit} = 0.15\left(\frac{E}{H}\right)\left(\frac{K_{Ic}}{H}\right)^2 \qquad [4]$$

Where:

- E: young modulus
- H: hardness
- Kk: fracture toughness

The other important value of mechanism is the tilt angle of the tool [5]
This parameter is highly important in cutting with milling tool, as the cutting speed depends on the tilt angle.

Effect of the tool's type on the cutting process

The other important research area of ceramics machining method is analysing of the cutting tool. E. Ferraris and her colleagues made experiment on ZnO_2 ceramics, where they analysed the lifetime of the applied tools. [4]
The experiment showed that the lifetime of a coated tool was 30 times longer than the lifetime of an uncoated tool.
The other interesting way of enhancing the lifetime of a cutting tool is the combined technology. Toru Kizaki and his colleagues mixed the conventional cutting technology with laser technology. [8]
In their experiment the cutting edge was heated with laser, so instead of machining in brittle zone they managed to achieve the plastic deformation zone. The result of their experiment was managing to decrease the cutting force with 35 percent.
On the whole it can be stated that in case the aim is to optimize the applied cutting technology for tools with longer lifetime, and machining of ceramics are economically efficient, only if "C_2" coated tools are used during the process. However, the cost of "C_2" coated tool is much higher than the basic coated tool', so we have to take into account the numb of manufactured products.

Tool path take effect on machining process

The literature doesn't detail the optimized toolpath for ceramics machining, so, in this article those toolpaths were presented shortly which will be the base of the application experiments. The paths which were used during the experiments was created using the of EdgeCam software [9]. The first analysed path was wave form, and the second was cycloid path. This software contains other path types, but these forms were not appropriate in the practical assignment because these don't allow to use various parameter settings.

Wave form

The wave form tool path (Figure 2. and 3.) for milling technology results that the tool is working with constant tool diameter sweep. Owing to this the tool load is constant in every changing direction during the machining through avoiding sharp changes in direction, which doesn't be found among the average path generation methods. [9]

Fig. 2: wave form [10]

Fig. 3: waveform toolpath [10]

The other advantage of the wave form strategy is that the value of material removal speed to be kept constant, compared to average path generation methods.
Cutting distributes wear evenly along the entire flute length, rather than just one the tip. The radial cutting depth is reduced to ensure consistent cutting force allowing cutting material escaping from the flutes. Tool life is further extended as most of the heat is removed in the chip.

Cycloid path

The other applicable toolpath was the cycloid path (Figure 4.).

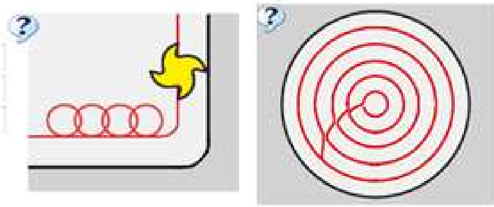

Fig. 4: cycloid path

The cycloid form is a milling technology where the tool milling is going along an arc, avoiding sharp changes in the direction. Although it doesn't control the tool engagement owing to cycloid form this strategy also can reduce the tool load, and the roughing strategy is optimized easier. The problem with the average toolpath is that tool load increase significantly in the corners requiring shallower depths of cut and reduced feed. This problem can be avoided with cycloid and wave form path.
Because the pocket was used during the experiment didn't have circle geometry so the technology was made optimized with entremets. The entremets is an option in the software which the tool load can be reduced more in the corner. The toolpath which was made with this method can be seen on 6th Figure.

III. EXPERIMENTS FOR THE MACHINING OF CERAMICS

The literature review mirrored that machining ceramics technology contain great number of parameter which have to be analysed, so, this results many difficulties to optimize this technology and to use it in the related industrial application area. For finding the optimal parameter combination a rough experiment plan has to be created to reduce the number of parameters. This experiment aims to get information about the ceramic cutting process, wearing of the tool, about critical point of the cutting process, time of pocket machining method. Moreover, another important aim was to get information about the appropriate tool path geometry and it's influence on the tool wear.

Parameters of the milling machine

The basis of the experiments was the milling machine that was planned and built by the CncTeamZeg group. The machine is operated by Mechatronics Institute of University of Pannon in Zalaegerszeg (Figure 5.). During the planning the aim was to cut metal material but after the preliminary calculations and first tests on ceramic material removal proved that the able to cut ceramic material, too.

Parameters of milling machine :

- Power: 1050 W
- Maximum tool diameter: 8 mm
- Speed : 5000-25000 1/min
- work area: 500x400x180 mm

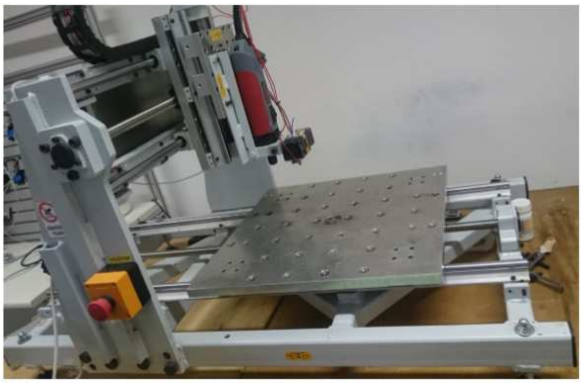

Fig 5: CNC machine

Experiments with wave form

During the first experiments wave form was used with linear axial cutting depth technology. Rapid tool wear process was observed. During the milling when tool takes the axial depth increasing cutting force was observed by sharp voice and glowing. Extrem wearing was perceived in this way. Consequently, the cycloid form seemed to be a better way in the following experiment processes.

Experiments with cycloid form

Because of the above mentioned reasons, in the second strategy cycloid path was used to machine the pocket in order to enable cycloid axial depth strategy.

Generated toolpath

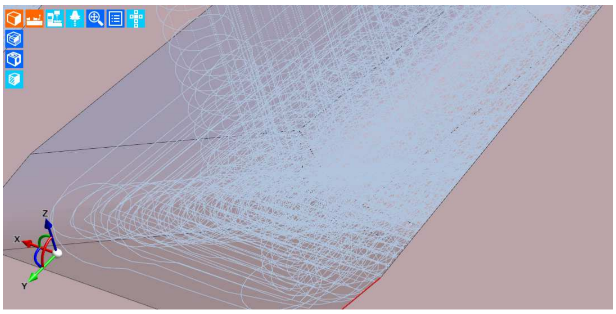

Fig.6: Generated toolpath

During the experiment coated tools were used. It was an economical reason why these tools were applied, because these preliminary tests did not aim to find the economically optimal solution, but to get the first basic experiences.

IV. RESULTS OF EXPERIMENT

After the experiments the lifetime was analised measured by the number of the successfully produced pocket. The wave form application resulted significant tool wearing in axial direction using axial cutting depth so the advantages of this form wasn't managed to exploit, but later on it will be a field of further research with appropriate extensions.
In the next experiment the strategy of cutting depth was optimized using the cycloid path so consistent wear was observed on the tool. Changing the strategy increased the lifetime with around 50 %. The resulted tools of the two experiments are presented in Figure 7.

Fig.7 : Tool after wave form, after cycloid form, unworn tool

These experiment show that optimized axial cutting depth strategy significant lifetime increasing was observed.

V. TASKS OF LINEAR AND NON LINEAR DESIGN OF EXPERIMENT

Tasks of linear design of experiments

The aim of the linear design of experiments (DoE, introduced by Professor Taguchi) is to describe the variation of process efficiency under varying machining conditions and to identify which machining parameters have the most influence on the analysed process.

Experimental design involves not only the selection of suitable influencing factors and outcomes, but planning the design of the experiment under statistically optimal conditions given under the constraints of available resources [7][11].
In this experiment the aim to find optimal parameter combination between tool life time and cutting time

Tested tools during linear DoE

<u>Two tools were analysed:</u>

- "C_1" coated milling tool
- "C_2" coated milling tool

Aim of comparison was to determine to what extent results other lifetime an type of "C_1" coated tool than type of "C_2" coated tool, which was suggest for machining ceramics by literature [12].

Examined parameters:

- measured machining time of 1 pocket (Tc)
- tool life time measured by the number of successfully produced pockets (Tnr)

Tasks of non linear design of experiments

During linear DoE it is not expected to determine a comprehensive model as function among the machining and process performance parameters. Based on the experiences of the linear DoE the most critical parameters are identified and in this space of selected variables a non-linear DoE is prepared [17], [18] in order to build up a multidimensional and is needed non-linear qualitative model for the process. With the iterative use of this model it is possible to find the optimal machining technology. In order to result in economically appropriate machining multicriteria optimisation is needed (e.g. considering process time, tool life and cost factors).

Other technology challenges that has to be analysed using the non-linear design of experiments:

- The hang over of the tool important diagnosis aspect;
- Air or water based cooling is appropriate?
- For diagnostic reasons the measurement and monitoring of the of cutting force, temperature and tool wear is required.

VI. CONCLUSIONS

The paper introduced an analysis of ceramic machining using regular cutting geometry. The following main results were described:

- Significant reduction in the number of process variables;
- Axial and radial cutting depth are the one of the most important variables which influence the life time of cutting tool;
- Analysis of the required time of machining one pocket beyond the tool life time.
- Incorrect choice of toolpath parameter causes significant diversion in life time;
- Using the wave form it is reached that the tool work along the entire flute length;
- It was proved that the pre-built machine at Mechatronics Institute of University of Pannon in Zalaegerszeg is able to perform the ceramic machining tests, too, beyond original planned the metal cutting.
- Two different tool path strategies were compared and evaluated.

Beyond the published results, an outlook was introduced for the future research to perform also non-linear DoE for building up quantitative process models in order to find the optimum point of the complete analysed industrial machining.

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VIII. REFERENCES

[1] Peter Janson "Modern gas turbine system." Woodhead Publishing Series in Energy: Number 20, 2013

[2] Muhammad Arif, Mustafizur Rahman, Wong Yoke San "Analytical model to determine the critical conditions for the modes of material removal in the milling process of brittle material" Journal of Materials Processing Technology 212 (2012) 1925–1933

[3] Muhammad Arif "Ultraprecision ductile mode machining of glass by micromilling process" Journal of Manufacturing Processes 13 (2011) 50–59

[4] Eleonora Ferraris, Jan Bouquet, Dominiek Reynaerts, Bert Lauwers, Heleen Romanus "Micromilling of sintered ZrO2 ceramic via CBN and diamond coated tools." Procedia CIRP 14 (2014) 371 – 376

[5] Kevin Foy, ZhiWei, Takashi Matsumura, YongHuang "Effect of tilt angle on cutting regime transition in glass micromilling." International Journal of Machine Tools & Manufacture 49 (2009) 315–324

[6] K. Ueda, T. Sugita, H. Hiraga "A J-integral Approach to Material Removal Mechanisms in Microcutting of Ceramics" (1991)

[7] Viharos, Zs. J.; Kis K. B. "Integrated Experimental design and parameter optimization under uncertain process circumstances", XXI IMEKO World Congress "Measurement in Research and Industry", August 30 - September 4, 2015, Prague, Czech Republic, ISBN 978-80-01-05793-3, pp. 1219 - 1224.

[8] Toru Kizaki, T. Ogasahara, N. Sugita, M. Mitsuishi "Ultraviolet-laser-assisted precision cutting of yttria-stabilized tetragonal zirconia polycrystal." Journal of Materials Processing Technology 214 (2014) 267–275

[9] http://www.edgecam.com/edgecam-waveform

[10] *Móricz László, Dr Viharos Zsolt János* "Kerámia marás optimalizálása és a megmunkálás aktuális

trendjei” Proc. of 26th ENELKO, pp. 105–110.

[11] G. Taguchi, Taguchi on Robust Technology Development: “Bringing Quality engineering Upstream” ASME Press, 1992.

[12] Rong Biana, Eleonora Ferraris, Ning Hea, Dominiek Reynaerts “Process investigation on meso-scale hard milling of ZrO_2 by diamond coated tools” Precision Engineering, 2014

[13] Chen-Tsu Fu,Jeng-Ming Wu “The effect of electro discharge machining on the fracture strength and surface microstructure of an Al_2O_3-Cr_3C_2 composite.” Materials Science and Engineering, A188 (1994)

[14] Lingfei Ji, Yinzhou Yan, Yong Bao, Yijian Jiang ” Crack-free cutting of thick and dense ceramics with CO_2 laser by single-pass process. “Optics and Lasers in Engineering

[15] Jiyue gong, Thomas J. Kim “An erosion model for abrasive waterjet milling of polycrystalline ceramics “ Wear 199 (1996) 275-282

[16] Jun Chenga,∗, Guoqiang Yina, Quan Wena, Hua Songb, Yadong Gong “Study on grinding force modelling and ductile regime propelling technology in micro drill-grinding of hard-brittle material. “ Materials Processing Technology

[17] Viharos, Zs. J.; Kis K. B. “Integrated Experimental design and parameter optimization under uncertain process circumstances”, XXI IMEKO World Congress “Measurement in Research and Industry”, August 30 - September 4, 2015, Prague, Czech Republic, ISBN 978-80-01-05793-3, pp. 1219 - 1224.

[18] Monostori, L.; Viharos, Zs.J. “Hybrid, AI- and simulation-supported optimisation of process chains and production plants “ , Annals of the CIRP, Vol. 50, No. 1, 2001, pp. 353-356.