

## THE STUDY OF CUTTING FORCES AND THEIR AMPLITUDES DURING HIGH-SPEED DRY MILLING MAGNESIUM ALLOYS

Ireneusz Zagórski<sup>1</sup>, Józef Kuczmaszewski<sup>1</sup>

<sup>1</sup> Department of Production Engineering, Mechanical Engineering Faculty, Lublin University of Technology, 36 Nadbystrzycka Str., 20-618 Lublin, Poland, e-mail: i.zagorski@pollub.pl; j.kuczmaszewski@pollub.pl

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### ABSTRACT

This paper presents the state of knowledge on cutting forces values during milling of different magnesium alloy types. Additionally, the results of own research on cutting forces and their amplitudes after milling magnesium alloys used for manufacturing elements applied in the aerospace industry are included. The subject of the analysis was the influence of technological parameters and the tool type on cutting forces and their amplitudes. The analysis is important due to the correlation between cutting forces and temperature in the cutting area, and, consequently, the safety of machining and strain of the workpiece.

**Keywords:** high-speed dry milling, magnesium alloys, aviation elements, machinability, cutting forces.

### INTRODUCTION

Aircraft structure elements made from magnesium alloys are commonly subjected to milling, in both roughing and finishing machining operations. Maintaining accuracy in shape and dimension of the workpiece is as significant as e.g. achieving the required surface finish quality, as it is related to such machinability indicators as temperature in the cutting area or cutting forces. Moreover, the aim is to reduce the processing time, which might be attainable with the application of appropriate methods of efficient high speed machining. The reason for applying efficient machining is the prospect of reducing processing time, increasing process efficiency and, as a result, reducing production costs.

High Speed Machining (HSM) is a term meaning machining with high speeds. HSM is defined as a high efficiency machining method which allows achieving high quality surface. Additionally, this type of processing is characterised by high parameters (feed per tooth, cutting speed) and low depth of cut. Consequently, a small chip cross-section and an enhanced chip removal are achieved. Increased cutting speed leads to an in-

crease in feed rate per tooth, which, in turn, induces a decrease in main time, which implies higher production efficiency of the process [1, 13].

What seems vital is the fact that during HSM the increase in cutting speed (with constant process efficiency) results in a reduction of cutting forces. Consequently, milling thin-walled elements (e.g. up to 0.1 mm) becomes possible [13]. A division into conventional machining and HSM is commonly assumed. According to that division, HSM occurs when an increase in cutting speed  $v_c$  leads to reduction in cutting forces, which may be expressed as follows [1]:

- $\partial F/\partial v_c < 0$  – HSM,
- $\partial F/\partial v_c > 0$  – conventional machining.

High efficiency machining (high productivity) includes HPM (high performance machining) or HPC (high performance cutting). HPC is a process which strives for optimal usage of the spindle for removal of large volumes of material per unit of time. Higher cutting speed  $v_c$  ensures increased process efficiency, but with the simultaneous occurrence of higher feed per tooth. It is argued that HPC is suitable for preliminary machining and profiling, while HSC excels in finishing [4].

For instance, the application of HSM allows to reduce (4 times) the processing time with no effects on the surface finish quality or shape accuracy [6]. Achieving the desired shape accuracy is possible due to reduced cutting forces during high speed machining.

## CURRENT STATE OF KNOWLEDGE

Great emphasis is placed on safety during machining of magnesium alloys. Improving material removal processing of magnesium alloys as well as widening magnesium alloys application range seems to be of great significance [9]. Common problems occurring during dry milling of magnesium alloys are as follows: [2, 7, 8, 10] risk of chip ignition, inaccurate shape and dimensions resulting from adhesive processes and flank built up (FBU), low wear resistance of the tool during milling of strengthened alloys as well as impeded chip removal outside the cutting area.

Cutting forces cause strain of the processed machine components. Additionally, so called deformations of chip thickness were found to increase with the increase of cutting forces. The shear angle decreases with decreasing undeformed chip thickness and, as a result, the shear plane temperature changes (increases). This phenomenon can be explained using the term appropriate cutting forces (appropriate cutting force is the correlation between the cutting force and chip cross-section). The cutting force increases with decreasing undeformed chip thickness. Shearing energy per unit volume increases the volume of removed metal when cutting forces increase causing an increase in cutting temperature in the shear plane [3, 5].

Both adhesion and flank built-up can induce high fluctuations of cutting forces as well as reduction of surface finish quality and accuracy in shape and dimension. When milling magnesium alloy AZ91HP using a tool with a PCD cutting edge with the application of oil cooling, cutting forces are low and they increase linearly with increasing feed rate [7]. PCD tools allow to obtain superior quality surface finish, lower cutting forces and are less prone to overheating due to low coefficient of friction in the tool – workpiece contact [11]. Due to lower cutting forces occurring during processing using tools with polycrystalline diamond cutting edges, especially with reduced cross-section of machined layers, considerably low temperatures are observed [2, 4, 7, 10, 11].

During processing with a Kordell design tool within technological parameters of ‘conventional’ machining, change in cutting speed  $v_c$ , induced higher values of cutting force components and their amplitudes in the case of casting magnesium alloy AZ91HP. However, with change in feed per tooth  $f_z$ , the components  $F_x$ ,  $F_y$  and their amplitudes increased along with an increase in feed. Higher values of cutting forces and their amplitudes, similarly as in the case of change in cutting speed  $v_c$ , were observed for the AZ91HP alloy [5, 12].

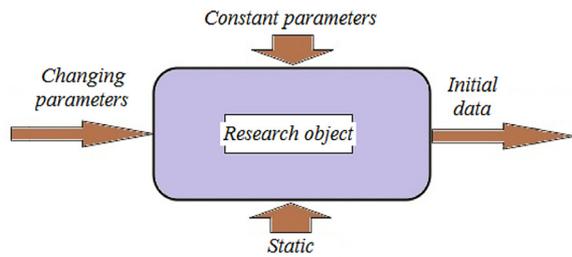
When machining with ‘classical geometry’ tools, cutting forces and their amplitudes are influenced by changes in feed per tooth  $f_z$ , rather than change in cutting forces  $v_c$ . The highest cutting force value was observed for AZ91HP alloy machined with a tool with a PCD cutting edge. Changes in feed per tooth induce an approximately linear increase in cutting force components and their amplitudes. Highest values of cutting force components  $F_y$  and  $F_z$  occurred with  $v_c=300$  m/min. What seems intriguing is that cutting force components decrease with cutting speed increasing up to  $v_c=400$  m/min. No considerable differences in cutting force values were observed for both AZ31 and AZ91HP alloys within the entire range of feed and changes in cutting forces [5].

## METHODOLOGY AND SCOPE OF RESEARCH

The main aim of the study was to analyse the effect of such parameters as cutting speed  $v_c$  and feed per tooth  $f_z$  on cutting forces and their amplitudes during machining AZ31 and AZ91HP magnesium alloys. Processing was performed on vertical machining centre Avia VMC800HS. The tools applied in the study were 16 mm end mills: carbide TiAlN coated, carbide Kordell design and one with a PCD cutting edge. A constant milling width  $a_c = 14$  mm and the following technological parameter ranges were used:  $a_p = (0.5-6)$  mm,  $f_z = (0.05-0.3)$  mm/tooth,  $v_c = (400-1200)$  m/min.

Forces were measured using a Kistler 9257B dynamometer and a 5017B amplifier. The dynamometer allows to measure forces from -5 kN to +5 kN. Cutting forces are defined as ‘functional’ indicators of machinability.

Figure 1 shows a plan for a research on the influence of multiple factors on cutting forces and their amplitudes. The changing parameters are as follows: cutting speed  $v_c$ , feed rate per tooth  $f_z$ ,



**Fig. 1.** Research plan for the analysis of cutting forces and their amplitudes in high-speed machining

type of tool material and type of workpiece material. Depth of cut  $a_p$  and cutting width  $a_c$  values were constant. Cutting forces ( $F_x, F_y, F_z$ ) as well as cutting force amplitudes ( $AF_x, AF_y, AF_z$ ) served as initial data.

Kordell design is characterised by three wave-shaped cutting edges. This type of tools is dedicated for processing aluminium alloys (so-called first choice) as well as magnesium alloys. Additionally, the characteristic features of Kordell geometry are helix angle  $\lambda = -40^\circ$ , maximal depth of cut  $a_p = (7-45)$  mm, no corner radius  $r_c$ , a positive rake angle  $\gamma = (9-12)^\circ$  for reducing cutting forces. Characteristic features of such a carbide Kordell design tool are presented in Figure 2.

The obtained results allowed finding the following correlations:

- maximum values of cutting force components  $F_x, F_y, F_z$  as a function of technological parameters of processing;
- maximum values of cutting force amplitudes  $AF_x, AF_y, AF_z$  as a function of technological parameters of processing.

## TEST RESULTS AND THEIR ANALYSIS

Figure 3 shows the time history of cutting force components  $F_x, F_y$  and  $F_z$  during milling of magnesium alloy AZ31 with a carbide TiAlN coated tool.

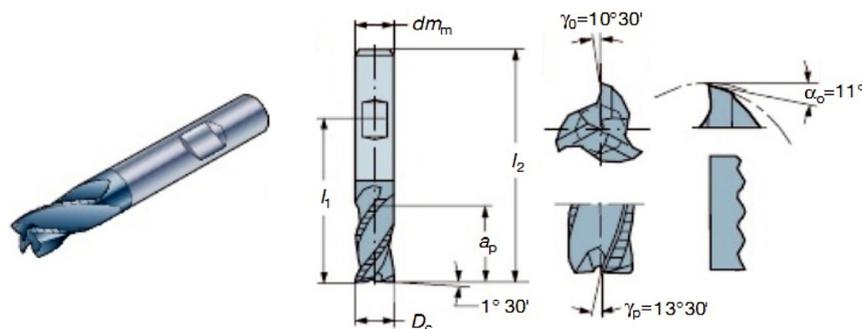
Figure 4 presents the effect of change in cutting speed  $v_c$  on cutting force component  $F_x$  and its amplitude  $AF_x$ . The influence is ambiguous. The decrease in cutting force and its amplitude most probably is a consequence of transition to HSM (increase in  $v_c$  – decrease in cutting forces). This correlation is observed for tools with so called ‘classical geometry’ of the cutting edge.

Figure 5 shows the effect of change in feed per tooth  $f_z$  on cutting force  $F_x$  and its amplitude  $AF_x$ . The cutting force component and its amplitude were found to increase with increasing feed per tooth. The increase in cutting force  $F_x$  and its amplitude  $AF_x$  is approximately linear.

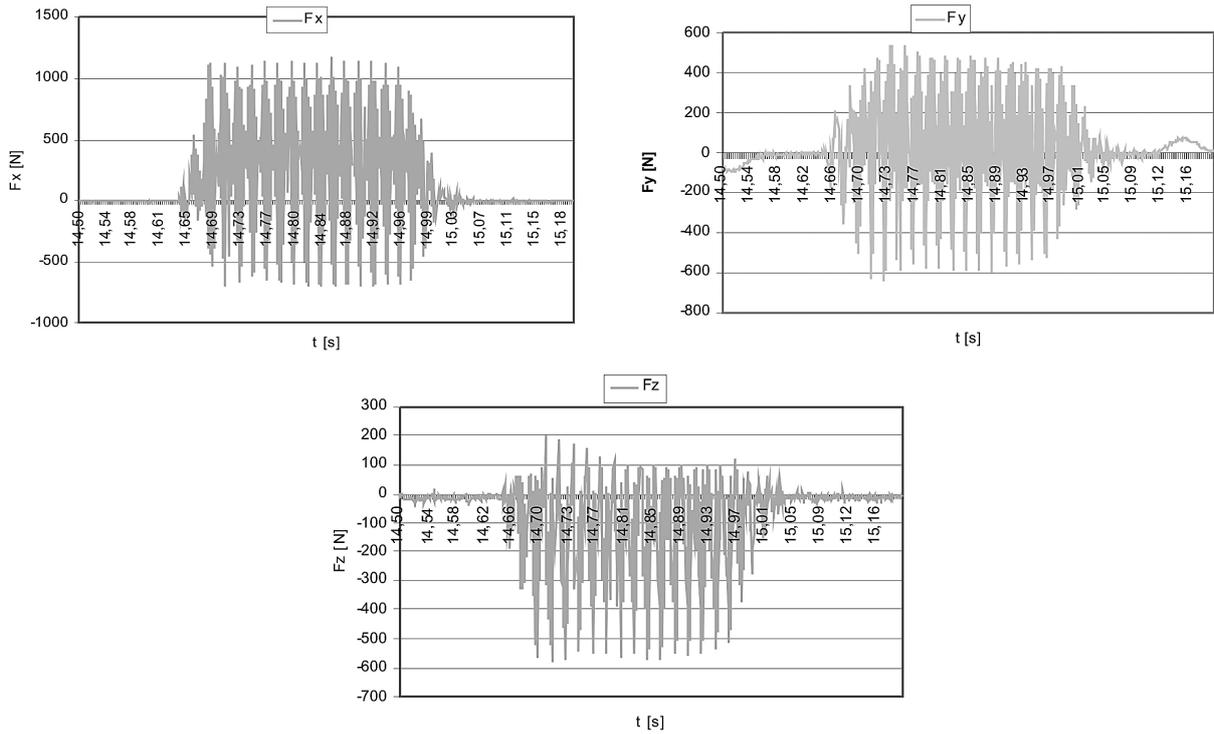
Figure 6 presents the influence of change in cutting speed  $v_c$  on cutting force  $F_y$  and its amplitude  $AF_y$ . The influence is ambiguous. In the case of ‘classical geometry’ tools, the force and its amplitude initially increase, but then begin to decrease. This process indicates transition to HSM. In the case of a Kordell design tool, the influence of change in cutting speed  $v_c$  is reverse.

Figure 7 shows the influence of change in feed per tooth on cutting force  $F_y$  and its amplitude  $AF_y$ . With the application of a tool with a PCD cutting edge as well as a Kordell design tool cutting speed and its amplitude increase along with the increase in feed per tooth. The increase in force  $F_y$  and its amplitude  $AF_y$  is approximately linear. A different influence of  $f_z$  is observed when a carbide TiAlN coated tool is applied. In this case, the force and its amplitude increase until feed per tooth reaches  $f_z = 0.15$  mm/tooth, for higher feed per tooth values, the force and its amplitude decrease.

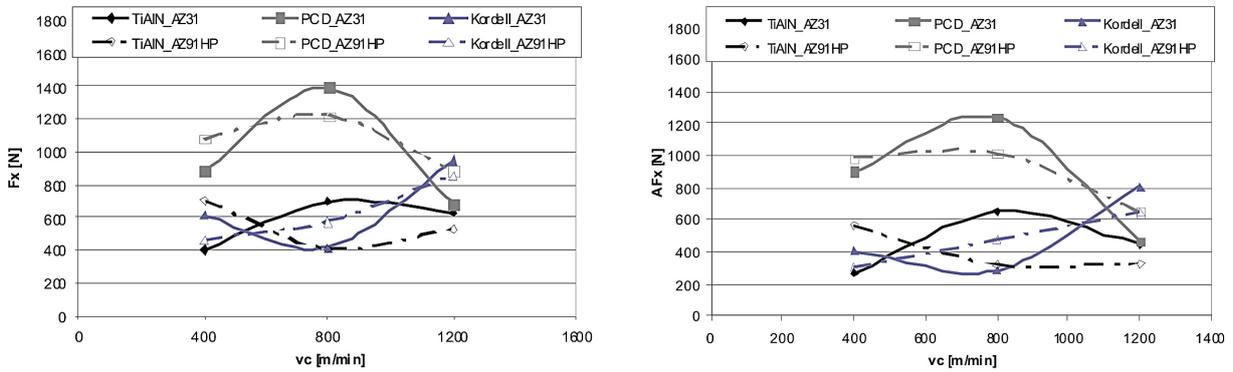
Figure 8 shows the influence of change in cutting speed  $v_c$  on cutting force  $F_z$  and its amplitude  $AF_z$ . In the case of ‘classical geometry’ tool, the force and its amplitude initially increase, but then begin to decrease, which indicates transition to HSM. In the case of a Kordell design tool, the influence of change in cutting speed  $v_c$  is reverse.



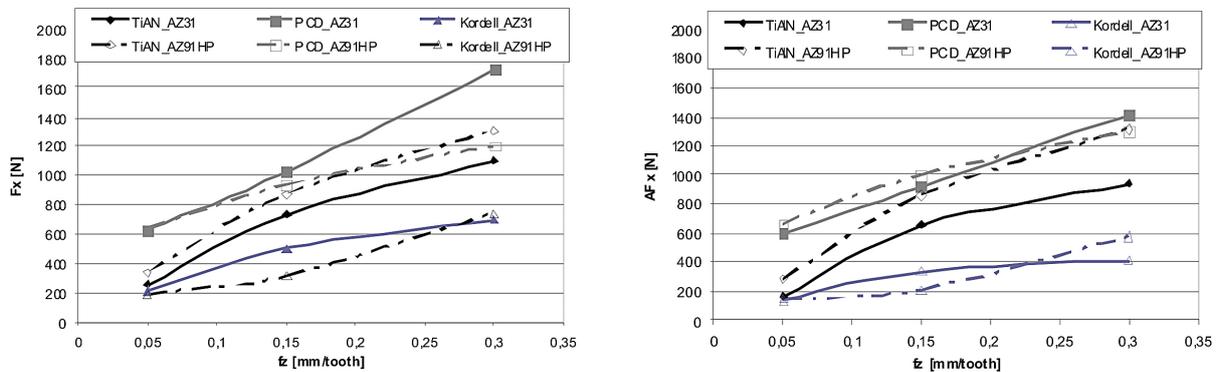
**Fig. 2.** Catalogue image of a Kordell end mill [14]



**Fig. 3.** Time history of cutting force components during milling of magnesium alloy AZ31 using a TiAlN coated carbide tool: a) component  $F_x$ , b) component  $F_y$ , c) component  $F_z$ ;  $v_c = 800$  m/min,  $f_z = 0.3$  mm/tooth,  $a_p = 6$  mm



**Fig. 4.** The effect of cutting speed  $v_c$  on the value of a) cutting force component  $F_x$  and b) its amplitude  $AF_x$  during milling of magnesium alloys AZ31 and AZ91HP using different tools;  $f_z = 0.15$  mm/tooth,  $a_p = 6$  mm



**Fig. 5.** The effect of change in feed per tooth  $f_z$  on the value of a) cutting force component  $F_x$  and b) its amplitude  $AF_x$  during milling of magnesium alloys AZ31 and AZ91HP using different tools;  $v_c = 800$  m/min,  $a_p = 6$  mm

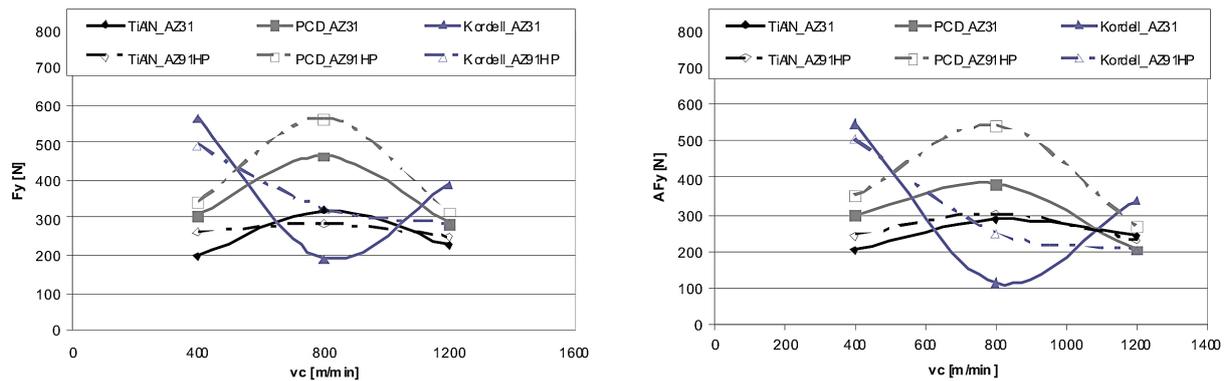


Fig. 6. The influence of change in cutting speed  $v_c$  on the value of a) cutting forces component  $F_y$  and b) its amplitude  $AF_y$  during milling of magnesium alloys AZ31 and AZ91HP using different tools;  $f_z=0.15$  mm/tooth,  $a_p=6$  mm

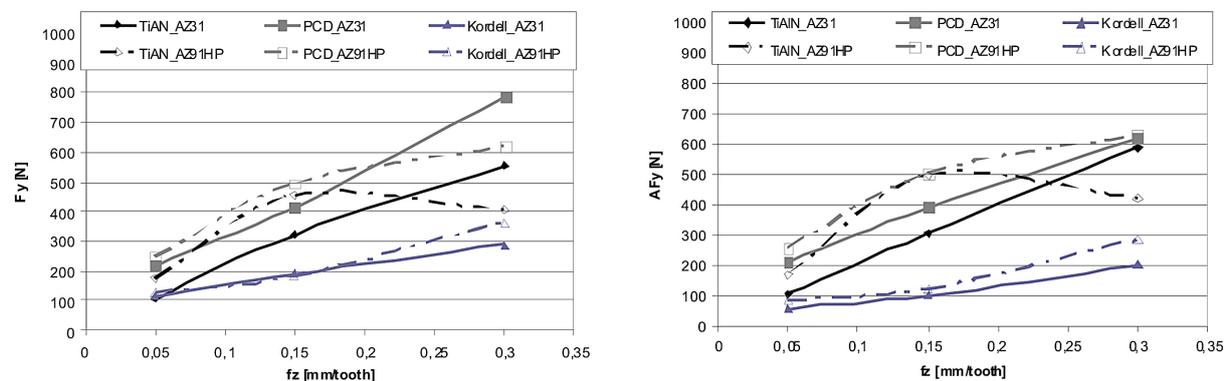


Fig. 7. The influence of feed per tooth  $f_z$  on the value of a) cutting force component  $F_y$  and b) its amplitude  $AF_y$  during milling of magnesium alloys AZ31 and AZ91HP using different tools;  $v_c=800$  m/min,  $a_p=6$  mm

Figure 9 shows the effect of change in feed per tooth  $f_z$  on cutting force  $F_z$  and its amplitude  $AF_z$ . Cutting force component and its amplitude was found to increase with increasing feed per tooth. The increase in cutting force  $F_z$  and its amplitude  $AF_z$  is approximately linear.

### CONCLUSIONS

The conducted analyses, study works as well as own research allow to formulate the following conclusions:

1. In high-speed machining it is feed per tooth  $f_z$  rather than cutting speed  $v_c$  which is of greater influence on cutting forces and their amplitudes.
2. In the majority of instances cutting forces were higher when the tool applied had a PCD cutting edge.
3. In the case of change in cutting speed  $v_c$ , cutting force components  $F_x$ ,  $F_y$  and  $F_z$  reached highest values (in the majority of instances) for cutting speed equalling  $v_c=800$  m/min.

This correlation applies when tools with ‘classical geometry’ cutting edges are used.

4. What might be found interesting is the fact that cutting force components decreased with cutting speed increasing to the value of  $v_c=1200$  m/min, in the case of tools with ‘classical geometry’ cutting edges.
5. An increase in feed rate per tooth causes approximately linear increase in cutting force components and their amplitudes.
6. No significant changes in cutting forces were observed with changing feed per tooth  $f_z$  in the case of magnesium alloys AZ31 and AZ91HP. The change occurred with changing cutting speed  $v_c$ .

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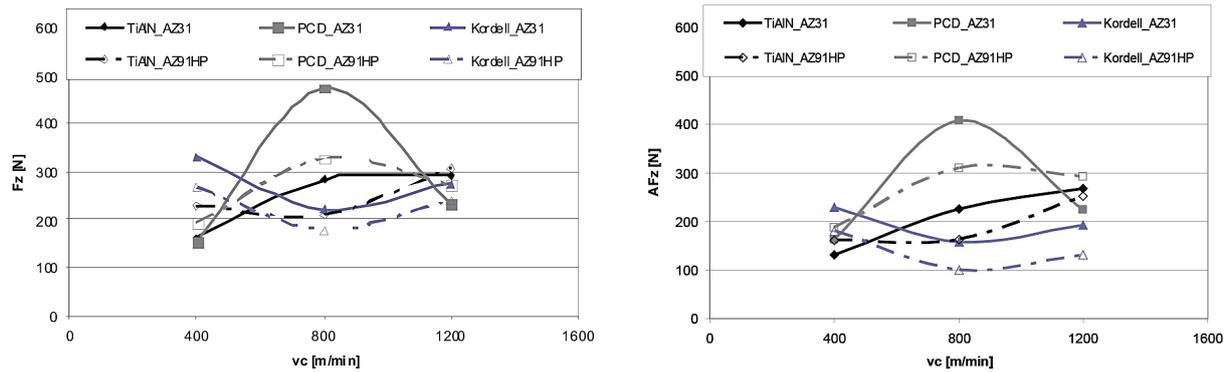


Fig. 8. The influence of cutting speed  $v_c$  on the value of a) cutting force component  $F_z$  and b) its amplitude  $AF_z$  during milling of magnesium alloys AZ31 and AZ91HP using different tools;  $f_z = 0.15$  mm/tooth,  $a_p = 6$  mm

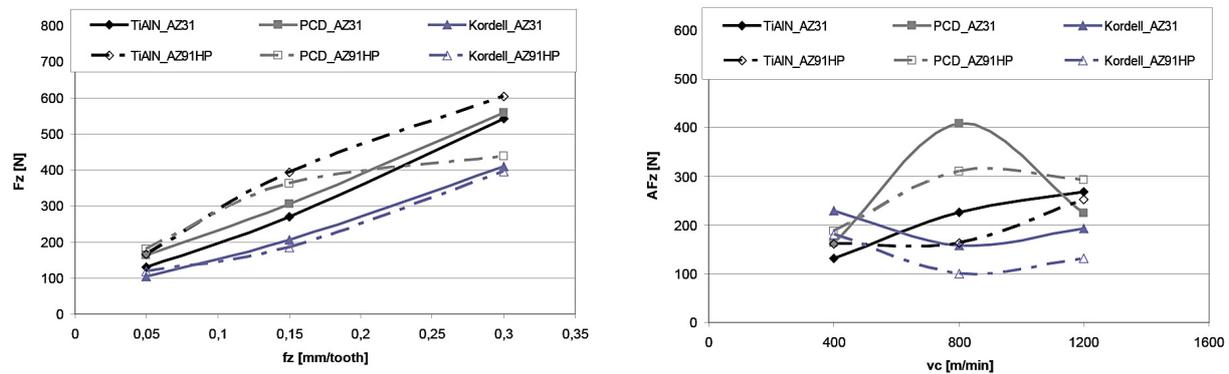


Fig. 9. The influence of feed per tooth  $f_z$  on the value of a) cutting force component  $F_z$  and b) its amplitude  $AF_z$  during milling of magnesium alloys AZ31 and AZ91HP using different tools;  $v_c = 800$  m/min,  $a_p = 6$  mm

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