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Safety in Rough Milling of Magnesium Alloys Using Tools with Variable Cutting Edge Geometry

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ABSTRACT

This paper presents the results of a study investigating the problem of safety in dry milling magnesium alloy AZ91D. Selected indicators of safe machining were analyzed, including time to ignition, ignition temperature, chip mass and morphology. Experiments were performed using carbide end mills with a variable edge helix angle. It was observed that magnesium alloys could be dry milled without the risk of chip ignition. The milling process conducted with the axial depth of cut a_p set to 6 mm was found to be optimum (a great amount of leading fraction A was produced). Unfortunately, however, some machining conditions proved to be inductive to the formation of chip powder known as magnesium dust. For most cases, chips obtained using the tool with λ_s 50° had higher unit mass than those obtained with λ_s 20°. Metallographic images of chips confirmed the safe range of the machining parameters employed (no partial melting or burn marks were observed). Determined on a specially designed test stand outside of the machine tool, time to ignition can be an effective parameter for performing simplified chip ignition simulations.

Keywords: magnesium alloys, rough milling, time to ignition, ignition temperature, chip mass, chip fractions, fragmentation.

INTRODUCTION

Both chip temperature in the cutting zone and ignition temperature are vital problems from the point of view of magnesium alloy machining safety. The first indicator (chip temperature) is usually determined via a direct cutting test performed on the machine tool. The other one (ignition temperature, time to ignition) is considered to be a secondary indicator, one that is impossible to determine via testing on the machine tool. Ignition temperature is usually determined on a specially designed test stand outside of the machine tool. Previous studies recommend determining the so-called ignition point, its value being different for every magnesium alloy grade.

It is generally claimed that machining temperature may be inductive to chip ignition and thus may cause machine tool damage and machine tool operator health hazard, and, as a consequence, pose a legal risk to the researcher in a scientific experiment [1]. The maximum temperature in milling magnesium alloys is achieved in a small chip formation area in the cutting zone and is directly related to chip formation time. Although some machining processes [2] are conducted with temperatures exceeding the so-called ignition point (approx. 500 °C for AZ91), chip ignition does not occur (in this context it is worth mentioning that the melting point for magnesium is approx. 650 °C). This lack of chip ignition during machining can be explained by a very short time of chip formation and a presumption that the ignition point was not achieved over the entire chip volume, but rather only on the contact surface between the chip and the tool rake. Generally, it can be claimed that the temperature generated in the cutting zone is inextricably linked to chip formation time, because at a later stage of the milling process the chip temperature does not increase. The problem of short-term ignition during milling and its infrared measurement [3, 4] has also been investigated in studies devoted to the machinability of other construction materials such as titanium or nickel alloys [5–8].

In machining processes, chip temperature in the cutting zone is usually measured with an infrared camera [2, 3, 4, 7, 9, 10, 11, 12]. For example, in the early years of the twenty-first century a study [9] conducted on milling AZ91HP alloy by the MQL method reported that the maximum chip temperature in this process was about 290°C. This value is lower than the melting point for magnesium alloys and the ignition point for fine particles (chips) (approx. 500 °C). Similar analyses were conducted for high-speed rough milling [2, 10, 11,12] to determine the maximum chip temperature during machining. When the milling process is performed using carbide end mills with standard cutting edge geometry [12], the temperature in the cutting zone is frequently below 350°C, therefore the milling process can be regarded as safe when conducted under these machining conditions. A similar observation was made for the carbide tool with a Kordell geometry end mill [10]. For most cases, the chip temperature did not exceed a value of 330 °C (for f_z=0.03 mm/tooth T_{max} was approx. 415°C). In contrast, the use of a PCD edge tool [2] may cause a short-term local temperature increase in the cutting zone even to above 500 °C. Nevertheless, no uncontrolled chip ignition occurred during machining, nor distinctive burn marks or partial melting were observed on the chip edges and surfaces. Similar studies (on chip temperature in the cutting zone) have also been conducted for other grades of construction materials used in industry. For example, chip ignition may occur during milling titanium alloys [5–8] and nickel alloys. Although the machining conditions and machining parameter ranges are considerably different from those used for light alloys, the risk of chip ignition and resulting machining problems are very similar.

Other solutions for measuring chip temperature during milling propose that the temperature be measured on the tool/workpiece contact [13]. As a result, it is possible to measure the mean temperature on the flank face. In HSC milling processes the mean flank temperature is not likely to be lower than that on the rake face (the so-called cutting temperature). Undeformed chip thickness is of the same order as the cutting edge radius. The flank mean temperature is measured with the use of a K-type thermocouple fixed to the workpiece. The measurement is made when the thermocouple gets damaged due to contact with the sharp cutting edge. It was found that there were no burn marks on the chips (mean flank temperature was about 302 °C). In [14] the effect of cutting speed on the mean tool flank temperature in milling AM50A alloy was studied. Measurements were made with the use of two K-type thermocouples. The milling process was conducted under high-speed machining conditions (v_c ≈ 3 014 m/min). Chip ignition occurred when the cutting speed v_c was lower than 1 507 m/min. In [15] the temperature distribution was examined with the use of an infrared thermometer and a platinum temperature sensor for the contact method. The study showed that the temperature of magnesium alloy AZ91C was reduced after exceeding a limit cutting speed value ($v_c \leq 452$ m/min). Interestingly, at the same time, the cutting zone temperature increased as a result of the cutting speed increase. No chip ignition was observed in the experiment. Other studies [16, 17] investigated the temperature in the cutting zone during milling magnesium alloy Mg-Ca0.8. The temperature was measured at the tool/chip section interface (across the chip) and in the subsurface. Although the measured temperature was close to 600 °C, the risk of chip self-ignition had to be ruled out due to the fact that the chip did not achieve that temperature over its entire volume or in the analyzed chip section (the temperature over the chip volume was 150–450 °C). Chips can undergo self-ignition during machining only if the melting point (516.6 °C) is achieved or exceeded over the entire chip volume or section.

As mentioned previously, chip ignition and its temperature are particularly vital problems in terms of safety in dry milling magnesium alloys. Studies on dry milling of magnesium alloys AM50A and AZ91D [18, 19, 20] showed that chip ignition could occur at small depths of cut (from several up to several hundred μm). Chip ignition can take the form of sparks, flares and ring of sparks. The results demonstrated that AZ91D alloy chips were more prone to self-ignition (compared to AM50A chips). Chips produced during the machining of these alloys can have various shapes: powdered chips, tubular helical chips, acicular helical chips, and long belt chips. Unfortunately, however, for studies conducted with the depth of cut value up to several dozen μm, the results do not reflect the actuals problems faced in industrial practice. Nevertheless, they provide an interesting insight into the problem and considerably broaden the knowledge about basic phenomena.

An interesting parameter describing machining safety is the ignition point of a given magnesium alloy grade. This parameter is measured outside of the machine tool usually on cubic test specimens by oxidizing the specimen surface in order to determine the start of oxidation and the temperature at which it occurs. As it was mentioned previously, every magnesium alloy grade can have a different oxidation point and thus a different oxidation temperature (ignition temperature). Previous studies on chip ignition temperature [21, 22, 23, 24] examines alloy additions such as Ce, Al and Y. Depending on the experimental details, AM50, AZ91D, AZ31 and WE43 were found to undergo self-ignition after exceeding a temperature of about 500 °C (for WE43 alloy chips, self-ignition did not occur even up to 750 °C).

An equally important problem in terms of machining safety is the morphology of chips [25], their shape [26, 27, 28] and mass [29] as well as the presence of partial melting on the chip surfaces and edges or lack thereof [30]. Previous studies [13] proposed that partial melting or burn marks on chip flanks should be detected via scanning electron microscopy (SEM). The above can only occur after the melting point is exceeded during machining. Other studies [25, 26, 29, 30] recommended that ignition temperature, particularly time to ignition, should be determined on a specially designed test stand, outside of the machine tool; however, these studies solely refer to chips produced during machining. Therefore, chip ignition conditions are very similar to those that may be present on the machine tool during a milling test conducted with specified machining parameters. Moreover, it is possible to detect burns or partial melting via standard optical microscopy by comparing metallographic images of chip edges or surfaces with ignition products which form a region known as a "cauliflower area". Magnesium alloy chips have a distinctive structure. Their one side consists of lamellar plate structures, while the surface of the other side is shiny and smooth. Lamellas are regular laminar structures that are usually arranged parallel to each other. Their shiny and smooth surface is a result of chip contact with the tool rake surface. Lamellas are formed as a result of chip curling and breaking during material decohesion and chip formation.

The literature review reveals that there are no studies investigating the effect of cutting edge geometry on the chip shape and size, chip fractions as well as chip ignition temperature and time to ignition. This study aims to fill this gap by demonstrating that there exists a relatively wide range of machining parameters, the use of which does not cause any significant increase in the risk of chip ignition and thus machine tool component damage.

METHODOLOGY, AIMS AND SCOPE OF THE STUDY

The primary scientific objective of this study was to investigate the axial depth of cut a_p in terms of its effect on the risk of chip ignition during machining due to the formation of fine chip fractions. The effect of the axial depth of cut a_p on the fragmentation of chips, their morphology (chip shape and type) and mass was investigated. Percentages of individual chip fractions were also determined. In addition to that, experiments were conducted to determine the time to ignition of selected chip fractions (which was the secondary objective of this study) and their ignition temperature. The aim of the experiments was to assess chip ignition risk in machining by "simulating" ignition outside of the machine tool. As reported in [26], the terms "chip fraction" and "chip fragmentation" can be useful for chip description. A fraction is a population of particles of given size or dimensions, while fragmentation refers to a phenomenon (usually undesirable) occurring during the machining process when, apart from the leading fraction (the biggest and most distinctive one), fractions of different chip shape and mass are formed. The leading chip fraction and intermediate chip fractions were distinguished based on the obtained chip shapes. Some guidelines on how to analyze chip shapes and fractions are given in the PN-ISO 3685:1996 standard; however, it must be remembered that the standard relates to machining conditions for steel turning. Therefore, as stressed in [31, 32], this classification should be treated like an example, especially given the fact that a great variety of chip types can be formed. Therefore, it is recommended developing a classification system for every real machining process, including the milling process for magnesium alloys.

This study investigated the effect of machining parameters (axial depth of cut a_p) and tool geometry (helix angle λ_s = 20° and λ_s = 50°) on the milling process for magnesium alloys. Fig. 1a shows a schematic diagram of the experimental set-up (research plan) with the object of the study (chips of AZ91D alloy) while Fig. 1b shows the chip ignition test stand [33].

The study was conducted using chips of the casting magnesium alloy grade AZ91D, as this alloy grade is widely used for both research purposes and practical industrial applications.

Chip mass was measured using the laboratory electronic balance Ohaus Discovery DV215CDM with a measuring accuracy of 0.00001 g (for the measuring range 0–81 g). Chip mass measurements were repeated ten times per each chip fraction (both for the leading and the intermediate chip fraction). After that, metallographic images of chips were captured using a digital microscope, VHX-5000 KEYENCE. Another stage of the study involved analyzing time to ignition. Measurements were made five times per each chip fraction. Both maximum temperature of the heating plate and its mean temperature measured for 90 seconds were determined. Measurements of the heating plate temperature were made with a mineral-insulated thermocouple of K type (TP-102a-120, type of mineral insulated thermocouple NiCr-NiAl). This thermocouple is used for measuring temperature in liquids and gases as well as on surfaces [34]. It mates with a UNI-T temperature meter, model UT-320, with a measuring accuracy of ±[0.2% + 0.6°C] for K, J, T and E thermocouples. Additionally, to identify chip ignition-preceding stages, images were captured with a high-speed camera, Phantom 9.1.

Chips were obtained in a rough milling process conducted using tools with a variable helix angle λ_s. The milling process was conducted on a vertical machining center AVIA VMC 800 HS. The tools were balanced with a balance grade of G2.5 using a rotational speed of 25 000 rev/min. Under this requirement, the allowable residual unbalance depending on the tool weight can be as low as 1 gmm. The residual unbalance of the tool with a diameter of 16 mm, z = 3 and a helix angle of λ_s = 20° was 0.42 gmm, while for the tool with a helix angle of λ_s = 50° it was 0.23 gmm. The range of machining parameters was selected for the most undesirable conditions in terms of ignition of small chips produced with different axial depth of cut values ranging from 0.5 to 6 mm. Other machining parameters were maintained constant (v_c = 800 m/min, f_z = 0.15 mm/tooth and a_e = 14 mm).

EXPERIMENTAL RESULTS AND ANALYSIS

Chip fractions

Tables 1 and 2 show the chip fractions obtained in the milling process (using the tools with λ_s = 20° and λ_s = 50°) conducted with a variable axial depth of cut a_p. The chips obtained with λ_s = 20° had the form of short tubular helical chips, brittle chips and spalling chips. For greater axial depths of cut, the leading fraction exceeded 80 % with the chips being bigger and thus characterized by a more desirable shape. In the machining process conducted with the a_p values of 1.5 mm and 3 mm one can additionally see the presence of magnesium dust, which is undesired. The chips obtained with λ_s = 50° can be classified into tubular helical chips, long belt chips, brittle chips and spalling chips. For this case, the presence of magnesium dust can be observed for every value of a_p, with the exception of a_p = 3.0 mm.

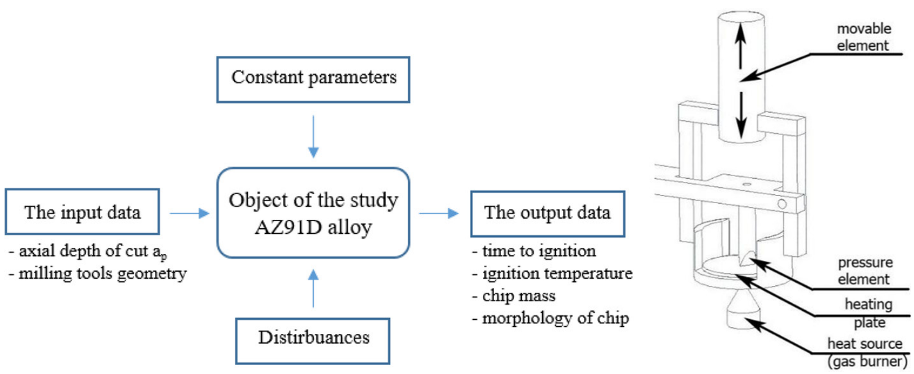


Fig. 1. Schematic diagram of: (a) experimental set-up (research plan with the object of the study) and (b) chip ignition test stand

Figure 2 shows the percentage of chip fractions obtained in milling conducted using the tool with λ_s 20°, while in Figure 3 with λ_s 50°.

From the point of view of machining safety, the most desired case is the machining process conducted with a_p = 6 mm because it produces the greatest amount of chips in leading fraction A, for both λ_s = 20° and λ_s = 50°. Similarly favorable conditions can be observed for a_p = 4.5 mm and λ_s = 20°. In other cases, a decrease in a_p results in increased individual intermediate fractions, together with the formation of a fraction called as powder chip.

Morphology of chips

The paper also presents examples of metallographic images of chips and their edges obtained for the extreme (maximum) values of the machining parameters. The images were captured using a digital microscope with a great depth of field.

In the images one can clearly observe that the chip elements (surfaces and edges) are free from characteristic areas of intense oxidation or ignition products (Fig. 4 and Fig. 5). For comparison purposes, we show the images of a surface subjected to intense oxidation or ignition with the characteristic products in the form of a "cauliflower area" on the chip surface and edges (Fig. 6).

Figure 6 shows the metallographic images of examples of ignition and surface oxidation products for magnesium alloy chips. The images show the presence of ignition areas with a characteristic "bundled" shape, known as a "cauliflower area". The identification of this area is significant in terms of machining safety. The presence of partial melting, burns or intense oxidation is characteristic of a machining area with chip ignition risk. The ignition point for common magnesium alloys (including AZ91) ranges approx. 500–600 °C and depends on the alloy type and grade. Therefore, chip ignition may occur after exceeding this conventional limit temperature known as the ignition limit [20–24]. An analysis of the chips does not indicate the presence of areas exposed to chip ignition because the chip edges are clear and there are no partial melting areas. Also, it should be remembered that self-ignition can be prevented by avoiding the accumulation of a great amount of chips in the machining zone.

Table 1. Chip fractions obtained with λ_s = 20°

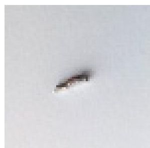
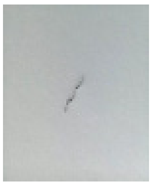
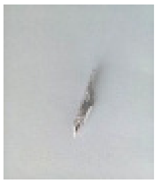
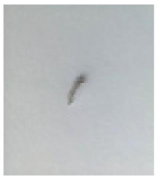
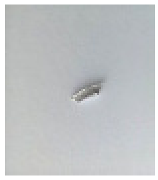
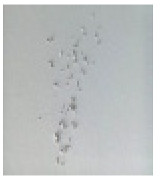
Type of chip fraction	Axial depth of cut a_p [mm]				
	0.05	1.5	3.0	4.5	6.0
Leading fraction A					
Intermediate fraction B					
Intermediate fraction C					
Intermediate fraction D					
Powder chip	None			None	None

Table 2. Chip fractions obtained with $\lambda_s = 50°$

Type of chip fraction	Axial depth of cut a_p [mm]				
	0.05	1.5	3.0	4.5	6.0
Leading fraction A					
Intermediate fraction B					
Intermediate fraction C					
Intermediate fraction D					
Powder chip			None		

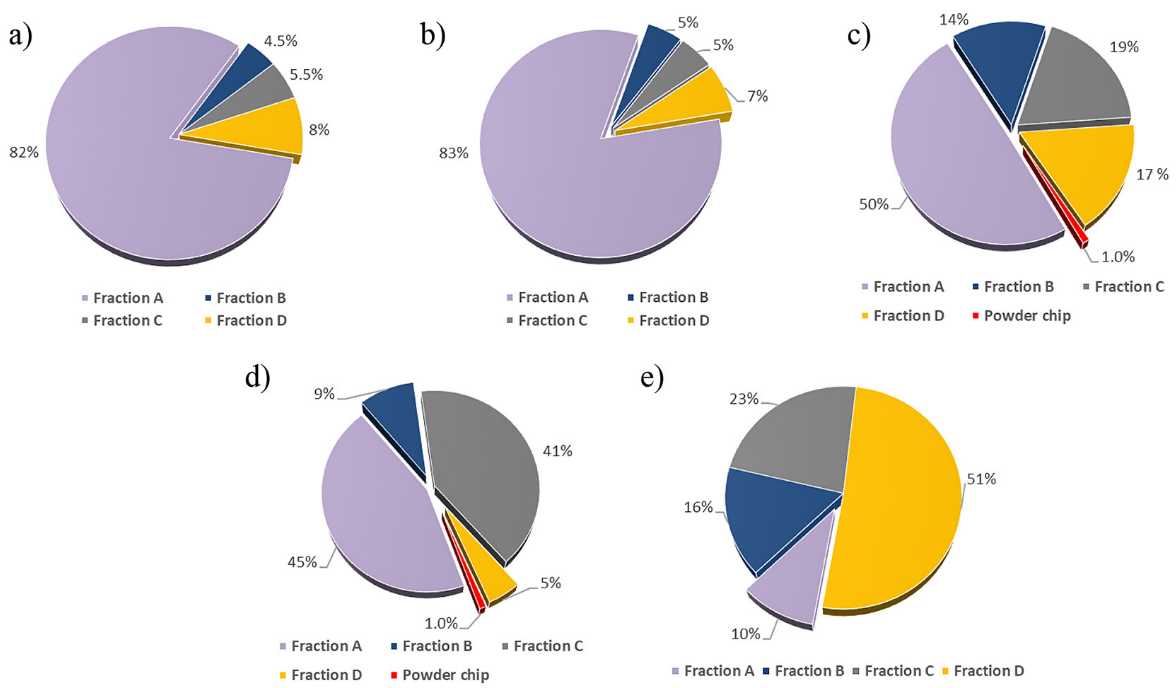


Fig. 2. Percentage of individual chip fractions obtained with $\lambda_s = 20°$:
a) a_p 6mm, b) a_p 4.5 mm, c) a_p 3 mm, d) a_p 1.5 mm, e) a_p 0.5 mm

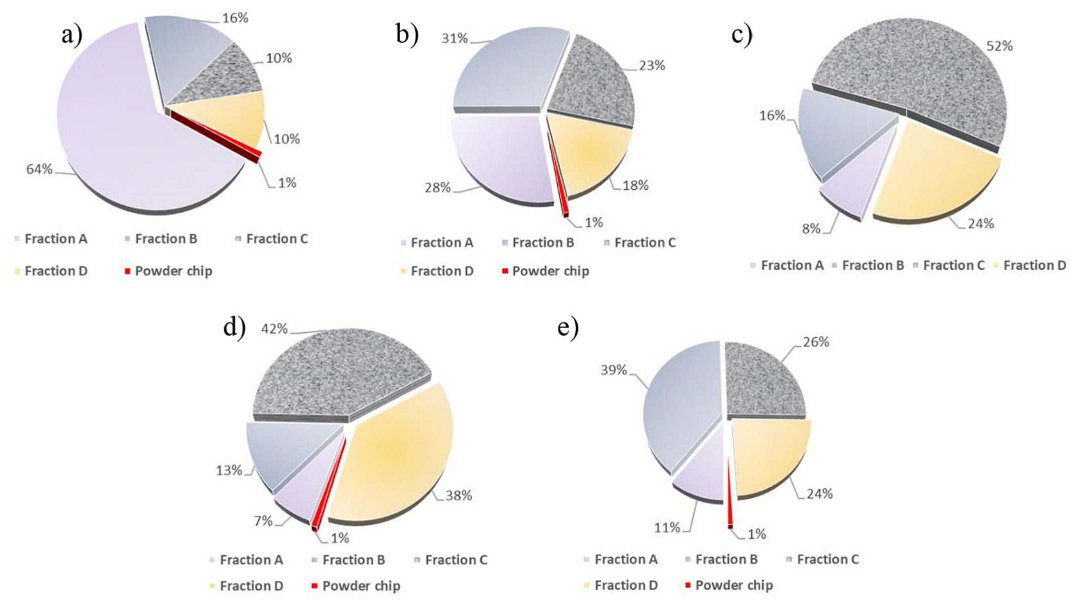


Fig. 3. Percentage of individual chip fractions obtained with $\lambda_s = 50°$: a) a_p 6mm, b) a_p 4.5 mm, c) a_p 3 mm, d) a_p 1.5 mm, e) a_p 0.5 mm

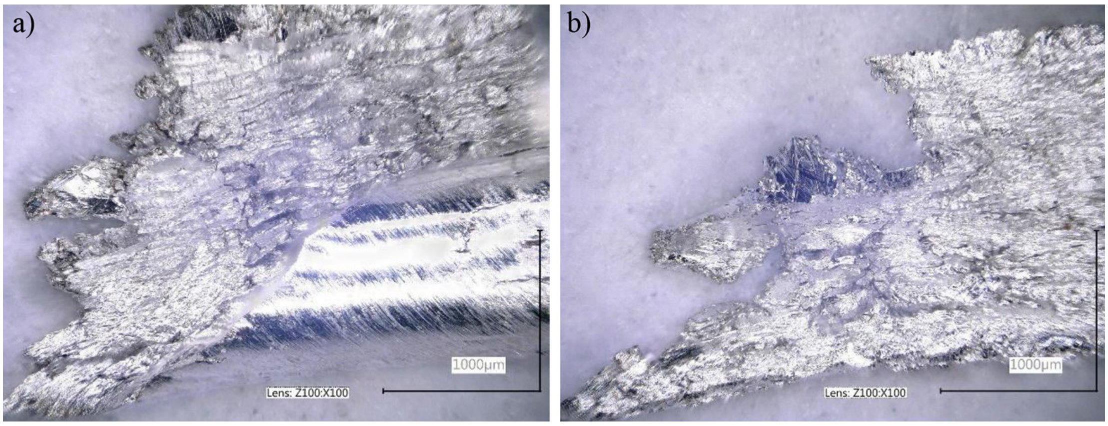


Fig. 4. Metallographic images of chips and their edges: (a) intermediate fraction B, (b) intermediate fraction D, $\lambda_s = 50°$, $a_p = 6$ mm; $f_z = 0.15$ mm/tooth, at 100 × 100 image resolution

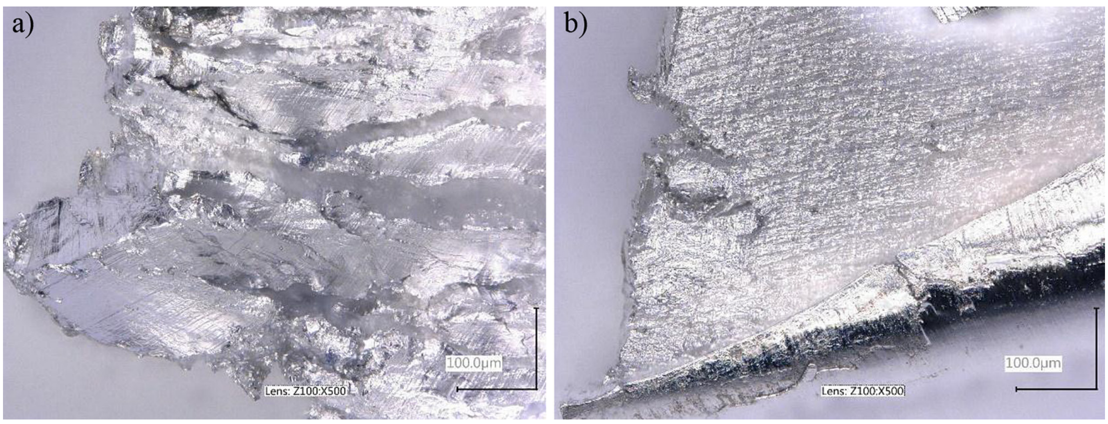


Fig. 5. Metallographic images of chips and their edges: (a) leading fraction A, (b) intermediate fraction D, $\lambda_s = 20°$, $a_p = 6$ mm; $f_z = 0.15$ mm/tooth, at 100 × 500 image resolution

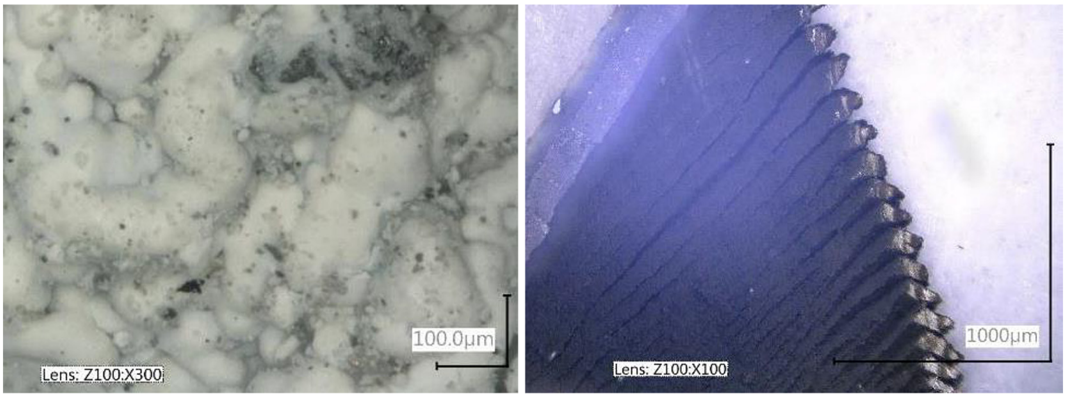


Fig. 6. Chips subjected to ignition or intense oxidation of surfaces and edges

Chip mass

Figure 7 shows the chip mass results obtained when milling using tools with a variable edge helix angle. It can easily be observed that the chip mass increases (in most cases) with the so-called cut layer section, i.e. (in this specific case) the axial depth of cut increase. The least favorable machining conditions (in terms of chip mass and fractions) are those which lead to the formation of so-called magnesium dust, i.e. for λ_s 20°: a_p = 3 mm and a_p = 4.5 mm, whereas for λ_s 50°: in the entire range of a_p without a_p = 3 mm.

Figure 8 shows the chip mass results with standard deviation for two chip fractions: A (leading) and D (intermediate). A comparison of the chips obtained with the two tools (within the same fraction) reveals that the chips obtained for the tool with λ_s 50° have (in most cases) a higher unit mass.

The greater unit mass of the chips obtained with λ_s 50° may be connected with higher deformation work that is required for chip decohesion. Due to their design, the tools with a higher helix angle have a different flute pattern. The tool with a helix angle of λ_s 50° has a greater helix angle in the tool axis than the tool with λ_s 20°. Generally, in light alloy machining it is important to make sure that the tool has the fewest possible cutting edges and the biggest possible flutes for effective chip removal. The flute capacity of the tool with λ_s 20° seems to be considerably greater than that of the tool with λ_s 50°.

Time to ignition, ignition temperature

Figure 9 shows the time to ignition of all chip fractions obtained at a_p = 0.5 mm and a_p = 6 mm. Fig. 9a shows the results obtained for λ_s 20° and Fig. 9b for λ_s 50°.

It can easily be observed that the time to ignition is considerably long compared to the time of chip formation. The time to ignition exceeds by several times the chip formation time which for the cutting speed range 400÷1200 m/min is between 0.01 and 0.001 s (for the mean v_c of 800 m/min, the time to ignition is only t = 0.002 s). For the cases shown in Figure 9, this time ranges on average up to several seconds.

Figure 10 shows examples of chip ignition-preceding stages following contact with the heating plate surface. The following stages can be

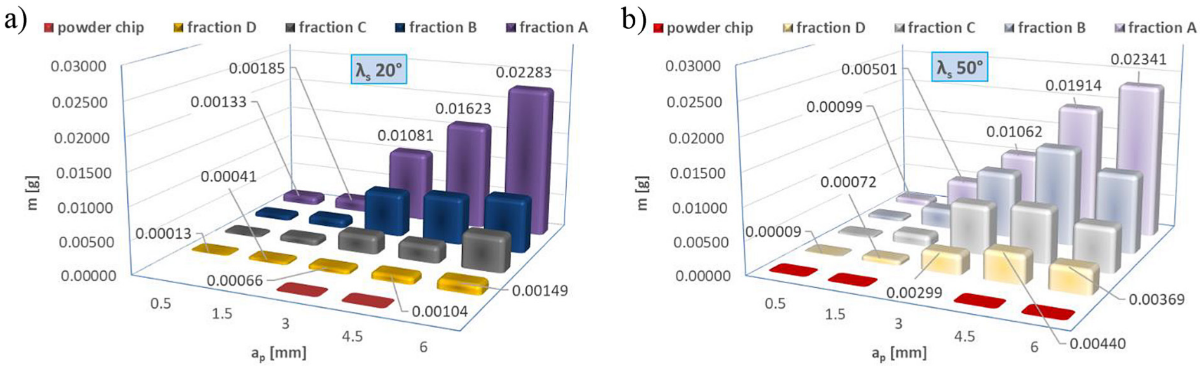


Fig. 7. Chip mass in all chip fractions obtained in milling magnesium alloy AZ91D: (a) for λ_s 20° and (b) for λ_s 50°

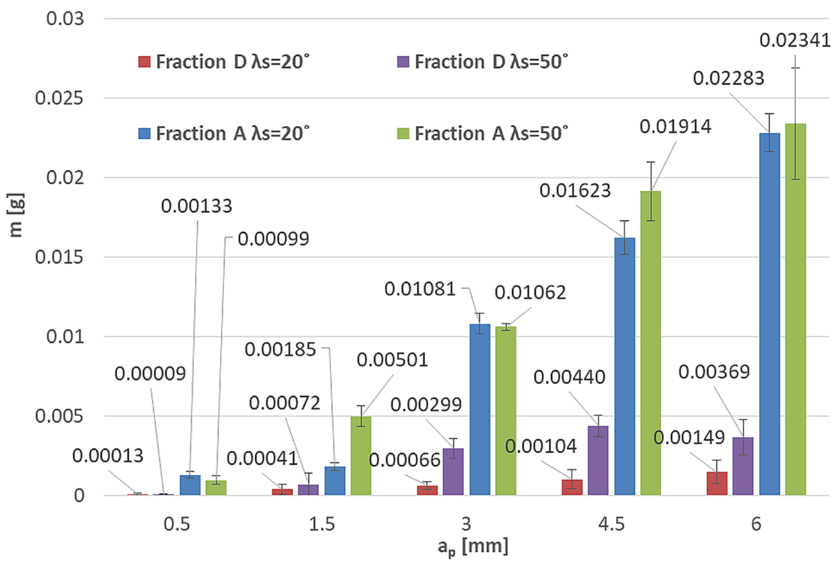


Fig. 8. Chip mass for fractions A (leading) and D (intermediate) with standard deviation

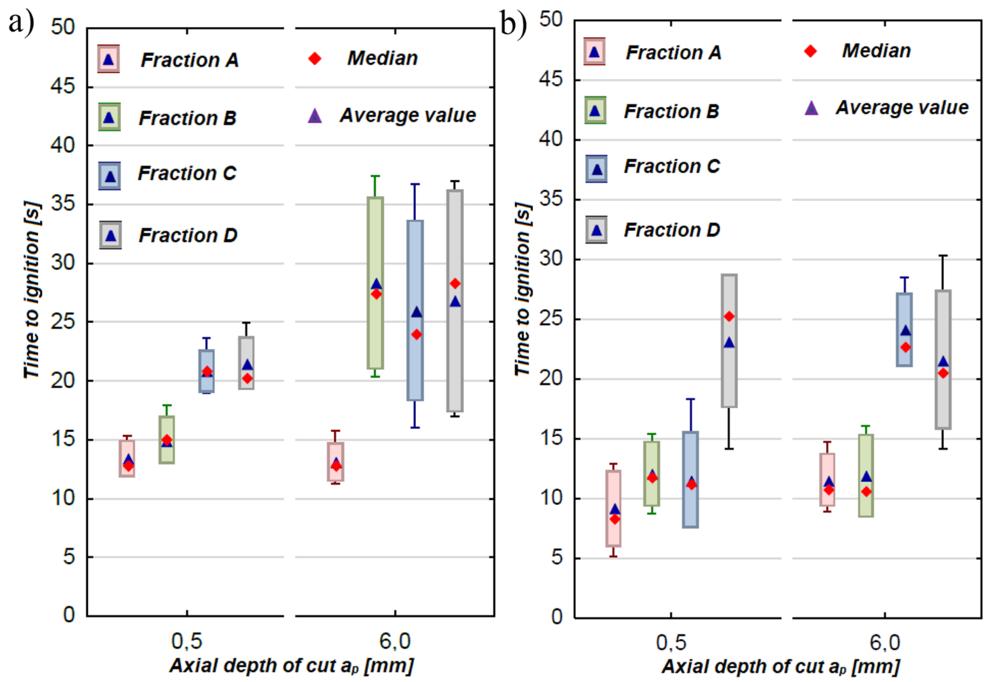


Fig. 9. Time to ignition for AZ91D chips: (a) for λ_s 20° and (b) for λ_s 50° (v_c = 800 m/min, f_z = 0.15 mm/tooth); (λ_s 20° – $T_{śr}$ = 437.9 °C, T_{max} = 443.6 °C – a_p 6 mm, $T_{śr}$ = 452.2 °C, T_{max} = 456.9 °C – a_p 0.5 mm) and (λ_s 50° – $T_{śr}$ = 450.3 °C, T_{max} = 470.4 °C – a_p 6 mm, $T_{śr}$ = 450.4 °C, T_{max} = 464.4 °C – a_p 0.5 mm)

distinguished: chip contact with the plate surface, partial chip plasticization, complete chip plasticization, chip ignition, as well as the formation of chip ignition and burning products.

CONCLUSIONS

The following conclusions can be drawn from the results of this study. The machining process conducted with a_p = 6 mm is the most effective and efficient because it generally produces a great amount of the leading fraction (fraction A), which is favorable due to a lower risk of ignition in the greater amount of smaller chips. For both λ_s 20° and λ_s 50°, certain machining conditions lead to the formation of chip powder known as magnesium dust. The formation of magnesium dust takes place when the machining parameters are as follows: for λ_s 20° a_p 3 mm and 4.5 mm, for λ_s 50° a_p 0.5 mm, 1.5 mm, 4.5 mm and 6 mm. The chips obtained in machining conducted with λ_s

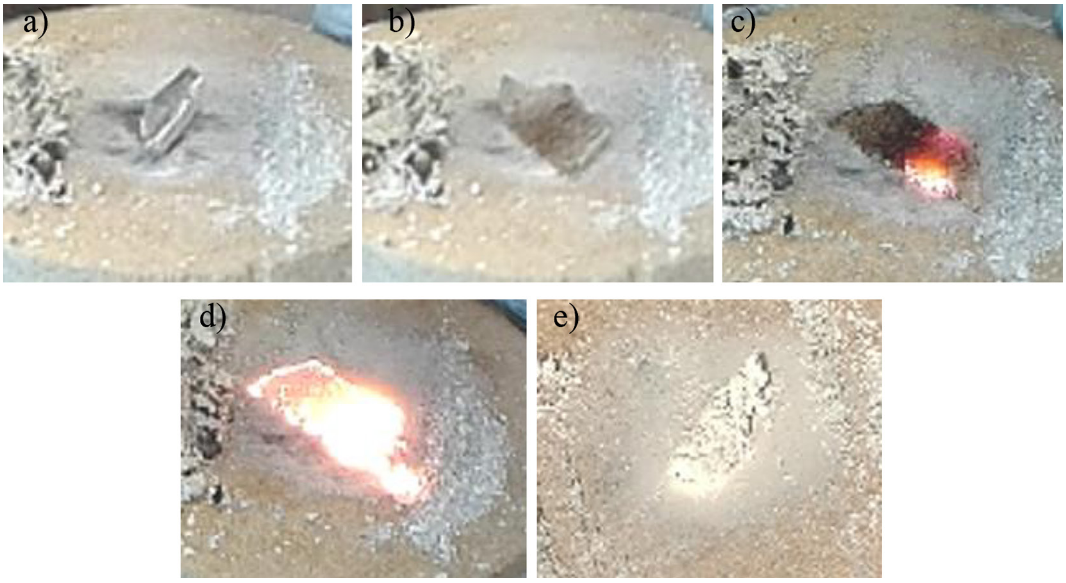


Fig. 10. Examples of chip ignition-preceding stages identified on the specially designed test stand equipped with a heating plate (for AZ91D alloy chips): a) chip contact with a plate surface, b) partial chip plasticization, c) complete chip plasticization, d) chip ignition, e) formation of chip ignition and burning products

50° have in most cases a higher unit mass than the chips obtained with λ_s 20°. The metallographic images show clear chip edges; the surfaces of the chips are free from products of ignition or intense oxidation, hence it may be concluded that the machining process conducted with these parameters can be considered safe. No chip ignition was observed during machining, not even under the conditions that led to the formation of the undesirable (from the point of view of machine tool operator health hazard and machine tool component life) magnesium dust, which confirms that the milling process is safe. Time to ignition measured on a specially designed test stand outside of the machine tool can be an effective parameter for chip ignition determination via performing simplified ignition simulations.

In spite of the fact that no higher risk of uncontrolled chip ignition has been observed, it is still important to maintain high technology standards in the machining zone. It is important to prevent excessive chip accumulation by successively removing machining products from the cutting zone. The technological parameters reported in this paper can be considered effective and safe; nevertheless, it is important to avoid machining conditions which are conducive to considerable chip fragmentation, particularly the formation of chip powder.

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