MACHINABILITY OF MAGNESIUM AND ITS ALLOYS

Birol AKYUZ
Bilecik University, Department of Mechanical and Manufacturing Engineering, 11200
Bilecik, TURKEY
birol.akyuz@bilecik.edu.tr

Abstract: Magnesium and magnesium alloys are used in a wide variety of structural applications including portable microelectronics and telecommunication, automotive, materials-handling and aerospace industries due to their low density. The utilization of magnesium alloys as automotive components is remarkably effective to reduce vehicle weight leading to both reduced discharge of air pollutants (i.e. CO_2, SO_X and NO_X emissions) and energy consumption. Another emerging area of Mg and its alloys are biomedical applications as biodegradable materials which may lead them to become next-generation materials.

One of the main drawbacks of the Mg and its alloys is their machinability since their chips during machining can be ignited suddenly leading to fire problems. Therefore, new machining methods have to be adopted for machining Mg and its alloys. The aim of this study was to review the machining methods of Mg and its alloys and evaluate the results as a function of their alloy composition and machining parameters.

Keywords: Machinability, Magnesium, Magnesium Alloys

INTRODUCTION

Magnesium and its alloys with a nominal density of around 1.8 g/cm^3, is one of the lightest structural metals, which have excellent mechanical properties, including high strength-to-weight and high stiffness-to-weight ratios. They are used in a wide variety of structural applications including portable microelectronics, telecommunication, automotive, materials-handling and aerospace industries due to their low density. The utilization of magnesium alloys as automotive components is remarkably effective to reduce vehicle weight leading to both reduced discharge of air pollutants (i.e. CO_2, SO_X and NO_X emissions) and energy consumption. Another emerging area of Mg and its alloys are biomedical applications as biodegradable materials that may lead them to become next-generation materials. In industry, commonly used magnesium alloys could be classified as AZ (aluminium, zinc), AM (aluminium, manganese) and AS (aluminium, silicon) series alloys (King, 2000).

Most magnesium parts are produced by casting processes. Thus, machining of functional elements is usually necessary. They have better machinability than other commonly used metals (Friedrich and Mordike, 2006; Mordike and Ebert, 2001). The machining could be performed under both dry and lubricated conditions. However, the powder-like chips are easily ignited. Therefore, the interest in magnesium and its alloys have grown dramatically in research community to identify new machining technologies in order to prevent ignition during machining as well as reducing their cost of production (Ruzi et al., 2009). Potential problems when machining of magnesium and its alloys are illustrated in Figure 1.

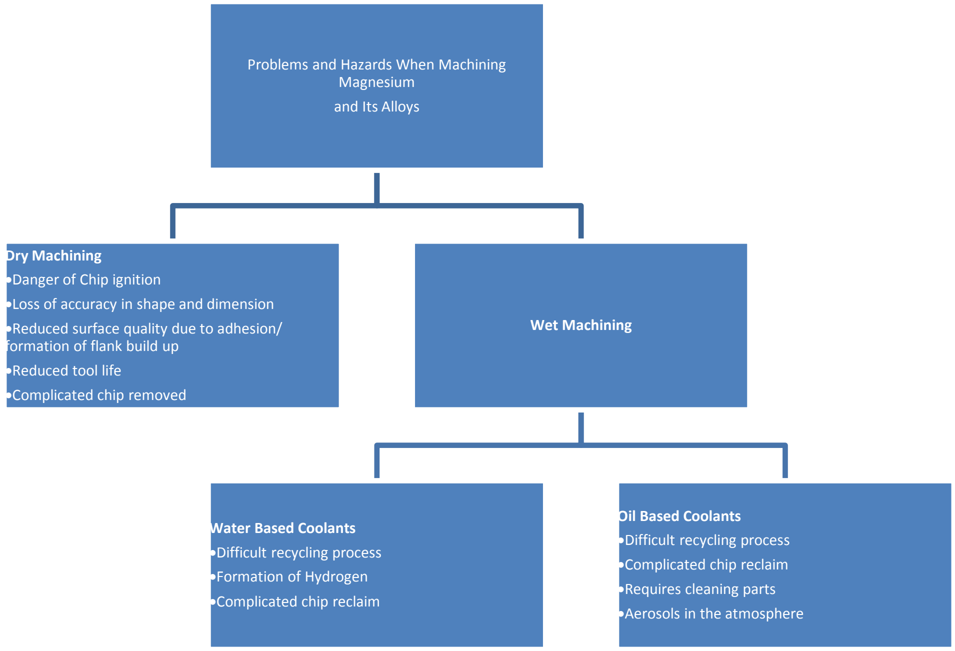


Figure 1: Problems and hazards when machining magnesium and its alloys

It is possible to achieve a high cutting speed for magnesium alloy, however, there are concerns that with an increase in cutting speed, there may be serious flank build-up (FBU) due to adhesion between the cutting tool and the workpiece as well as ignition problems. This may cause machining problems related to vibration and tolerances as well as the thermal expansion of magnesium may lead to an insufficient accuracy in geometry and shape of the machined part (Hou et al.,2010). Tönsoff and Winkler carried out turning experiments on the AZ91HP alloy. They observed that FBU due to adhesion between cutting tool and workpiece can occur at cutting speeds of 900 m/min when machining magnesium in dry condition. Friemuth et al. reported chip temperature and the danger of chip ignition could be reduced due to low machining forces when using polycrystalline diamond tools in dry machining of magnesium alloys. Tomac et al. indicated that FBU on cutting edges at speeds in excess of approximately 600 m/min might constitute a problem when turning magnesium alloys. Tomac et al. has also reported that the presence of intermetallic $Mg_{17}Al_{12}$ (β) phase in magnesium matrix is responsible for the difference in the machinability of magnesium alloys. Reported experimental tests have revealed that surface defects such as cracks and pores may promote the formation of the FBU problem (Tomac et al , 2008). Fang et al. presented an experimental study of the mean temperature on the flank face for predicting the occurrence of fire in high speed cutting of magnesium alloys. Ozsváth et al. used a new thermo-vision method to examine the chip temperature on rotating milling tool. Arai et al. proposed a method of the chip control by skiving of magnesium alloys and investigated cutting conditions experimentally for generating tubular helical chips, which were not ignited easily.

Viewing the literature published in the academic journals, it can be seen that the research on machining of magnesium alloys mainly focused on the FBU, operation speeds, cutting depth and composition of the alloys affecting the ignition of the chips, accuracy and shape of the machined part. Therefore, this report is intent to discuss the issues of machining of magnesium alloys from the cutting depth, FBU and alloy’s composition point of view.

Machinability of Magnesium Alloys

Cutting Depth and Speed

The machining is characterized by short-breaking chips, high achievable surface qualities, low-cutting forces, low mechanical and thermal loads on the tool (Denkana et al., 2005). Hou et al. analyzed the influence of depth of cut and cutting speed on ignition condition for AZ91 and AM50A magnesium alloys. In their work (Hou, et al., 2010) chips obtained at different cutting parameters were collected and the resulting data were compared. Thus, the analysis of the relationship between chip morphology and ignition were carried out. Table 1 and Table 2 present ignition conditions of chips at various cutting depths and speeds respectively.

Table 1: Ignition condition of AM50A and AZ91D chips at different cutting depths (Hou, et.al., 2010)

Condition of Ignition	Cutting Depth (µm)	
	AM50	AZ91
Sparks	20 30 40 50 60	---
Ring of Sparks	-----	2 5 7 10 15
Flare	2 5 7 10 15	20 30 40 50 60

Table 2: Ignition condition of AM50A and AZ91D chips at different cutting speeds (Hou, et.al., 2010)

Condition of Ignition	Cutting Speed (m/min)	
	AM50	AZ91
No	251	---
Sparks	503	251, 503
Ring of Sparks	---	628, 754, 880
Flare	628, 754, 880, 1005, 1257	1005, 1257

It is evident from the Table 1 that the ignition of the chips in the form of sparks initiates at the higher cutting depths and at lower cutting speeds for AM50 alloy. Transition from sparks to ring of to the flares takes place at higher cutting speeds and higher depth of cuts. Figure 2. shows appearance of sparks and flares during machining of AM50A and AZ91 alloys.

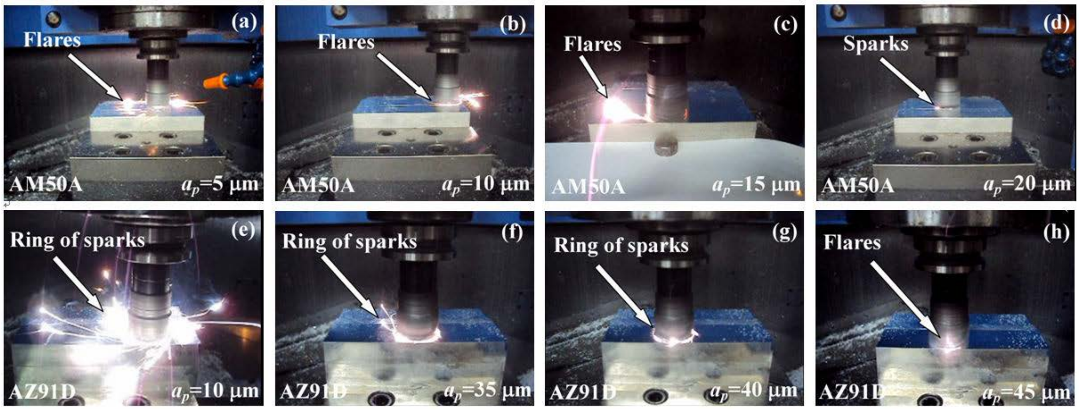


Figure 2 : Ignition conditions at different depth of cut during milling AM50A and AZ91D (Hou, et.al., 2010)

In AM50 alloys, 0.2% manganese is added in order to improve its corrosion resistance (Jönsson and Persson, 2010). Aluminium in AM50 alloy, however, results in hardness increase due to solid solution effect that have a negative effect on the machinability of the workpiece material, leading to a FBU and deterioration of the machined surface (Fang, et al., 2005). It is noted from the work of Hou (Hou, et.al., 2010) that ignition of AM50 alloy takes place without showing rings of sparks. However, the inanition of ignition follows formation sparks, ring of sparks then the flare in AZ91 alloy as the cutting speed and cutting depth increased.

It should be taken into account that small, powder like chips and their accumulation is not only a fire hazard, but can also damage machine tool components by polluting sensible areas in dry machining conditions. Furthermore, high process temperature leads to a reduced shape and dimension accuracy of the workpiece and a lower surface quality. For this reason, the concept of lubrication by different solutions as non water-mixable and water-mixed cool-lubricants become favorite. The advantages of the different concepts are briefly summarized here (Ozsváth et al., 2008; Fang, et al., 2005; Tikal et al., 2000):

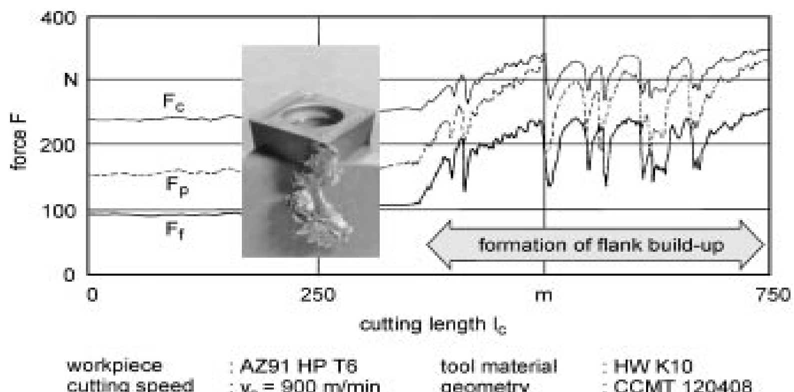
- Removal of chips.
- Keeping clean the machines.
- Decrease of the tool-wear.
- Avoidance of spark- and dust-formation.
- Lubrication of ways.
- Better heat removal.

However, there also are the dangers of the wet cutting. Through high cutting-speeds, deflagration-danger exists with the oil-treatment (Tikal et al., 2000). With the machining under application of water-mixed emulsion, hydrogen originates in the workroom and in the chip-conveyor. Hydrogen has a low ignition point that should be taken into account. If a fire occurs with the magnesium-treatment with emulsion, the burning magnesium reacts intensively with water. But not only these security-misgivings but also health, ecological and economic aspects should also be taken in to account.

Another problem appears with the recycling of the chips produced by wet machining (Hanko et. al., 2004). The chips, in case of application of lubricants, have to be cleaned first and dried afterwards. If the chips are to be briquetted, the diminution of the fire-danger between formation and recycling, the increased expenses must be considered. (Ozsváth et al., 2008; Tikal et al., 2000).

Flank Built Up (FBU)

In turning operations, strong adhesive effects between work piece material and most tool materials can be observed at high cutting speeds. This may cause machining problems related to vibration and tolerances that leads to an insufficient quality of the machined surface. Another major concern is the danger of fire ignition when dry machining magnesium alloys (Guo and Salahshoor, 2010). Fires may be prevalent when the melting point (400–600^{0}C) is exceeded. As this constitutes a serious problem in an industrial situation, it is necessary to be able to ascertain the temperature during cutting. A study on the measurement of the mean temperature on the flank face in high speed dry cutting of magnesium alloys has been reported (Denkana et al., 2004). Figure 1. illustrates the tool-travel dependent process force components, which are cutting force F_C, force in feed direction F_f and passive force F_p, when dry machining of AZ91D using uncoated cemented carbide. At a critical tool travel of l_{ckrit} = 350 m, significant variations of the forces were observed, which resulted from FBU attaching to and detaching from the tool flanks (Denkana et al., 2004; Tönsoff and Winkler, 1997).



α	γ	λ	ε	κ	$r_ε$
7°	5°	0°	80°	50°	0.8 mm

Figure 3. Formation of flank build-up (FBU) (Friemuth and Winkler, 1999).

The peak forces of the cutting force F_c exceed the force level before FBU by approximately 45%. For a safe and lowered FBU in the machining of magnesium, usage of coated tools has been reported (Lin et al.,2008; Denkana et al., 2004; Tönsoff and Winkler, 1997). The diamond coatings consist of a low reactivity, a good thermal conductivity and low friction properties against magnesium and its alloys (Ozsváth et. At, 2008). In dry machining, critical concerns such as the heat transfer, adhesion and FBU's can be prevented by usage of coated tools successfully (Ozsváth et al., 2008; Tikal et al., 2000). In a certain range, the surface of the tool influences the machined workpiece surface. Therefore, smooth chemical vapor deposited-diamond polycrystalline (CVD-DP) coatings are in development (Tikal et al., 2000; Tönsoff and Winkler, 1997). Adhesion can be observed on the uncoated cemented carbide grades and TiN-coated inserts. After a cutting length of approx. l_c = 350 m, adhesion leads to a FBU problem. Good results are achieved when machining magnesium with DP-tipped an CVD-DP-coated inserts (Lin et al.,2008; Denkana et al., 2004). The formation of FBU can be eliminated by the use of a suitable cutting fluid or a polycrystalline diamond (PCD) tool. Burnishing operations are a useful mean to improve surface quality, surface hardness and to induce compressive stresses in the subsurface layers if adequate burnishing conditions are chosen.

There is also a relation between tool coatings and cutting speed. In low speed cutting, the coating of the cutting tool is found to be removed due to a high cutting force, resulting from low cutting temperature, and abrasion dominates tool wear (Denkana et al., 2004). When the cutting speed is increased, a protective layer resulting from the diffusion of the cutting tool starts to form on the chip-tool interface. This layer works as a diffusion barrier. Hence, tool wear rate is reduced and the usable life of the tool is prolonged. However, when the cutting speed is further increased, cutting temperature becomes the dominant factor instead of the cutting force. The high cutting speed causes inhomogeneous shear strain, and a transition from continuous chip to saw-tooth chip occurs.

The influence of different cutting tool geometries on cutting and backing forces as well as surface formation in turning is affects the FBU. Therefore, optimizing of rake angles is also in consideration in order to reduce FBU and high cost of coated tools (Gariboldi, 2003). Uncoated carbide tools and tools with polycrystalline diamond (DP) tips as well as TiN and diamond coated carbide tools with different rake angles have been reported (Ozsváth et al., 2008; Fang et. al., 2005; Denkana, 2000). FBU can be avoided by using adapted clearance angles or coated tools. The use of cooling lubricants is another possibility to improve FBU and therefore surface characteristics but may cause the danger of ignition of hydrogen that can be formed when magnesium reacts with water based coolants. The use of oil should be avoided because of difficult chip handling and higher costs.

Alloy Compositions

Adding alloying elements is one of the effective methods to prevent the ignition of magnesium alloys. The formed heterogeneous phases, formed by alloying additions, can cause discontinuity in the matrix weakening the cohesive forces at the locations of discontinuity, which facilitates the easy breaking of chips during the machining process. Aluminium is the main alloying addition to magnesium matrix (e.g to AZ, AM, AS series). The maximum solubility for aluminium in magnesium in the solid state is 12.7% at 436°C and goes down to 2% at ambient temperature. In the cast condition the β phase is formed along the grain boundaries of the magnesium matrix (Lin et. at., 2010). This is especially the case if the cooling rate after processing is relatively low, e.g, in sand casting. It has been reported (Tomac et.al, 2008) that the critical cutting speed increases with decreasing aluminium content. It has been reported that the addition of rare-earth elements, such as yttrium and cerium, into alloys has been used to improve their oxidation resistance (Hanko et. al., 2004) implying that the ignition resistance also has been increased. For instance, the ignition temperature of AZ91D magnesium alloys can be much increased by the addition of cerium (Lin et. at., 2010).

CONCLUSIONS

Literature review highlighted the problems encountered with the machining of magnesium and its alloys are summarized as follows:

- One of the main drawbacks of the Mg and its alloys is their machinability since their chips during machining can be ignited leading to fire problems.

- Dry machining produces high temperature that promotes adhesion between cutting tool/work material as well as FBU when critical cutting speed is exceeded.

- With the machining of magnesium alloys under application of water-mixed emulsion, hydrogen generation results in fire and health hazards. With the wet machining, deflagration danger still exists with the oil-treatment at higher cutting-speeds.

- FBU is initiated by a certain affinity between cutting tool/work materials, sufficient cutting temperature, and the existence of hard particles embedded in the soft matrix.

- Coating of the tool, such as Polycrystalline diamond, helps diminishes formation of FBU's.

- The influence of different rake angles on cutting and backing forces as well as surface formation in turning affects the FBU.

- The form of ignition could be sequenced as spark, ring of sparks and flare depending on cutting speed, depth and composition of the magnesium alloy.

- The ignition of the chips in the form of sparks initiates at the higher depth of cuts and at lower cutting speeds for AM 50 series alloys. Transition from sparks to the flares takes place at higher cutting speeds and higher depth of cuts in AZ 91 series alloys.

- The ignition of chips can be impeded as aluminium content of the magnesium increased especially at finer cutting depths and higher cutting speeds.

ACKNOWLEDGEMENTS

The author would like to thank to Prof. Dr. Ercan CANDAN for discussion and support.

REFERENCES

1. B. Denkana, F.Witte, C.Podolsky and A.Lucas: Degradable Implants made of Magnesium Alloys, Proc.5Th. Euspen International Conferance-Montpiller, France, May 2005.
2. B. Denkena, J. C. Becker, C. Podolsky, and A. Kuhlmann: Safe Machining of Magnesium Parts by Cutting and Burnishing Operations, (Edited by K.U. Kainer), Magnesium Proceedings of the 6th International Conference Magnesium Alloys and Their Applications, Wiley-VCH, Germany, 2004.

3. B. L. Mordike and T. Ebert: Magnesium – applications – potential, Journal of Material Science Engineering A 302, pp. 37-45, 2001.
4. E. Gariboldi: Drilling a magnesium alloy using PVD coated twist drills, Journal of Materials Processing Technology 134, p.287-295, 2003.
5. F. Tikal, M. Schmier and C. Vollmer: High-speed-drilling in AZ91 D without Lubri-coolants, (Edited by Mordike and Kainer), Manesium Alloys and their Applications, WILEY-VCH Verlag GmbH, Weinheim, Germany, 2000.
6. F.Z. Fang, L.C. Lee and X.D. Liu: Mean flank temperature measurement in high speed dry cutting of magnesium alloy, Journal of Materials Processing Technology 167 ,119–123, 2005.
7. G. Hanko, C. Lochbichler, W. Riederer and G. Macher: Techniques for Recycling of Magnesium Scrap, (Edited by K.U. Kainer) , Magnesium Proceedings of the 6th International Conference Magnesium Alloys and Their Applications, Wiley-VCH, Germany, 2004.
8. H.E. Friedrich and B.L.Mordike: Magnesium Technology, Springer-Verlag Berlin Heidelberg, Germany, 2006.
9. H.K.Tönsoff and J.Winkler: The Influence of Tool Cutting in Machining of Magnesium, Surface and coating Technology,94-95, p.610-616, 1997.
10. J. F. King: Development of Practical High Temperature Magnesium Casting Alloys, Magnesium Alloys and their Applications. (Edited by B.L.Mordike and K. U. Kainer),WILEY-VCH, Weinheim, Germany, p.14-22, 2000.
11. J. Hou, W. Zhou and N. Zhao: Methods for Prevention of Ignition during Machining of Magnesium Alloys, Key Engineering Materials Vols. 447-448,pp 150-154, 2010.
12. M. Arai, S. Sato, M. Ogawa and H.I Shikata: Chip Control in Finish Cutting of Magnesium Alloy, Journal of Materials Processing Technology 62, 341–344, 1996.
13. M. H.Ruzi , M.Norhamidi, S.Abu Bakar, R.J.Khairur, M.N.Nor Hafiez, A.Sufizar and I.I.Mohd Halim Murtadhahadi: A Review Of Workability Of Wrought Magnesium Alloys, Advanced Manufacturing Research Group’09 Seminar 3, Advanced Manufacturing Research Group, 2009.
14. M. Jönsson and D. Persson: “The influence of the microstructure on the atmospheric corrosion behavior of magnesium alloys AZ91D and AM50, Swerea KIMAB, Drottning Kristinas väg 48, SE-104 05 Stockholm, Sweden, 2010.
15. N. Tomac, K. Tønnesen and T. Mikac: Study of Influence of Aluminium Content on Machinability of Magnesium Alloys, Strojarstvo 50 (6) 363 – 367, 2008.
16. P. Lin, H. Zhou, N.Sun, W. Li, C. Wang, M. Wang, Q. Guo and W. Li: Influence of cerium addition on the resistance to oxidation of AM50 alloy prepared by rapid solidification, Corrosion Science 52, 416–421, 2010.
17. P. Ozsváth, A. Szmejkál and J. Takács: Dry milling of magnesium based hybrid Materials, Transportation Engineering. Vol. 36, p. 73, 2008.
18. S. Y. Lin, S. H. Yu and M. L. Wu: Effect of Different Coating Materials on Cutting Performance in High-Speed Machining of Mold Steels, Key Engineering Materials Vols. 364-366, pp 1026-1031, 2008.
19. Y.B. Guo and M. Salahshoor: Process mechanics and surface integrity by high-speed dry milling of biodegradable magnesium–calcium implant alloys, CIRP Annals - Manufacturing Technology 59, 151–154, 2010.