CODEN STJSAO ISSN 0562-1887
ZX470/1359 UDK 620.179.118:621.91.025.1:669.721.5:539.42

Study of Influence of Aluminium Content on Machinability of Magnesium Alloys

***Nikola TOMAC*[1], *Kjell TØNNESSEN*[2] and *Tonči MIKAC*[3]**

1) Pomorski fakultet, Sveučilište u Rijeci (Faculty of Maritime studies, University of Rijeka),
Studentska 2, HR-51000 Rijeka,
Republic of Croatia

2) University of Trondheim, Department of Production Engineering, and SINTEF Production Engineering, Trondheim,
NTNU 7491 Trondheim, **Norway**

3) Tehnički fakultet, Sveučilište u Rijeci (Faculty of Engineering, University of Rijeka),
Vukovarska 58, HR-51000 Rijeka
Republic of Croatia

tomac@pfri.hr

Keywords

Flank build-up
Machining
Magnesium

Ključne riječi

Lažni vrh
Magnezij
Obrada

Received (primljeno): 2008-01-25
Accepted (prihvaćeno): 2008-10-31

Original scientific paper

This paper describes an experimental investigation on the formation of flank build-up (FBU) during the machining of five commercial magnesium alloys. It was demonstrated that the presence of intermetallic *β*-phase in magnesium matrix is responsible for the difference in the machinability of magnesium alloys. Experimental tests have revealed that surface defects such as cracks and pores may promote the formation of the FBU. The influence of cutting speed on the FBU formation was studied with the aid of surface roughness, tool forces, and chip form.

Ispitivanje utjecaja sadržaja aluminija na obradivost magnezijevih legura

Izvornoznanstveni članak

U ovom članku se opisuje eksperimentalno istraživanje formacije lažnog vrha na leđnoj površini alata za vrijeme obrade pet komercijalnih magnezijevih legura. Prikazano je da prisustvo intermetalnih *β*-faza u magnezijevom matriksu odgovorno za razliku u obradi magnezijevih legura. Eksperimentalna testiranja su otkrila da greške u materijalima, kao što su pukotine i pore, mogu pospješiti formiranje lažnog vrha (FBU). Utjecaj brzine rezanja na formiranje lažnog vrha je ispitivana uz pomoć površinske hrapavosti, sile alata i oblika strugotine.

1. Introduction

It is well known that the magnesium alloys are among the easiest of all structural metals to machine. It has been reported that a disadvantage of magnesium alloys is the fire risk which may be involved in the finish cutting operations at high cutting speeds. The fine chips must be heated near the melting point of magnesium (≈ 650 °C) for ignition to occur [1].

We have observed that when cutting certain magnesium alloys at high cutting speeds with cemented carbide tools, without the cutting fluid, a material build-up forms on the flank surfaces of the tool [2]. The formation mechanisms are principally of the same type as the classic build-up edge (BUE) which forms on the rake face of the tool. The term “flank build-up” (FBU) will be used in this paper.

Material build-up on the flank surfaces of the tool requires more frequent adjustment of machining parameters and replacements of the tool inserts with consequent1y higher tool costs and “down time”. Despite a large number of magnesium alloys with different chemical and physical characteristics, and considerable variations in their microstructures, Emley [3] has drawn the conclusion that there is no important difference in their machinabilities. A number of turning tests have shown that material build-up may be formed during machining certain magnesium alloys when the cutting speed exceeds a critical limit. However, the same phenomenon has not been found during machining an AZ-31 magnesium alloy under identical cutting conditions at all examined cutting speeds. From the work carried out so far it was not completely clear why some alloys should produce the FBU while others do not. The work presented in this paper was performed in an effort to better understand the effects of chemical composition, microstructure, and physical and chemical properties of the magnesium alloys on the FBU formation, with a further objective to improve the machining process of magnesium castings. The effect of changing cutting speed on the FBU formation was examined and the results interpreted in terms of associated change in the surface roughness of the generated surfaces and the tool forces. Special attention was paid to the detection of cutting speed in turning operations when the FBU is formed.

2. Experimental Procedures

Five commercial magnesium alloys have been machined in cylinder form according to the CIRP recommended cutting conditions for finish machining tests. The chemical compositions of the alloys are listed in Table 1.

Table 1. Chemical composition, wt % of the workpiece materials

Tablica 1. Kemijski sastav, wt % ispitivanog materijala

ALLOY	%Al	%Mn	%Zn	%Si	%Cu	%Fe
AM 20	2.0	0.25	0.01	0.0049	0.0010	0.0092
AZ 31	3.0	0.20	0.05	0.0100	0.0013	0.0084
AS 41	3.9	0.31	0.05	0.8900	0.0010	0.0074
AM 60	6.0	0.21	0.01	0.0081	0.0012	0.0155
AZ 91	8.4	0.22	0.63	0.0111	0.0030	0.0030

The effect of different alloying additions on tensile properties and average hardness of magnesium alloy are collected in Table 2. From Table 2 it can be seen that the strength and hardness of magnesium cast alloys increase with the increase of aluminium content while the ductility decreases. Microhardness and characteristic elements of phases which constitute the microstructure are given in Table 3.

Ground and polished discs of the workpiece materials were examined with an optical micro-scope. For comparison, typical microstructures are depicted in Figure 1.

Aluminium, which is the main alloying element in the examined magnesium alloys shows a decrease in solubility in the solid state, as its proportion increases. When the content of aluminium exceeds 3 %, the massive β-phase intermetallic compounds appear in the cast structure [4]. From Table 2 it can be seen that the presence of the relatively hard and brittle β-phase causes the strength and hardness to increase while the ductility decreases considerably. A network of the β-phase forms around the grain boundaries (Figure 1E). Visually, the β-phase is easily distinguished from the magnesium matrix, the β-phase appearing darker than the surrounding matrix. The massive β-phase compounds have a lamella form and appear in a discontinuous pattern.

Table 2. Effect of different alloy additions on mechanical properties of magnesium alloys

Tablica 2. Utjecaj legirajućih elemenata na mehanička svojstva magnezijevih legura

ALLOY	Tensile strength MPa	Yield strength MPa	Elongation %	Hardness HV 10
AM 20	185	105	12	47
AZ 31	260	200	15	49
AS 41	220	150	4	56
AM 60	220	115	6	56
AZ 91	230	150	3	75

Table 3. Microhardness of characteristic phases of AZ91 of magnesium alloys

Tablica 3. Mikrotvrdoća karakterističnih faza AZ91 magnezijevih legura

CHARACTERISTIC PHASES	MICROHARDNESS HV5g
MnAl particle	805
β-phase ($Mg_{17}Al_{12}$)	270
Mg matrix	68

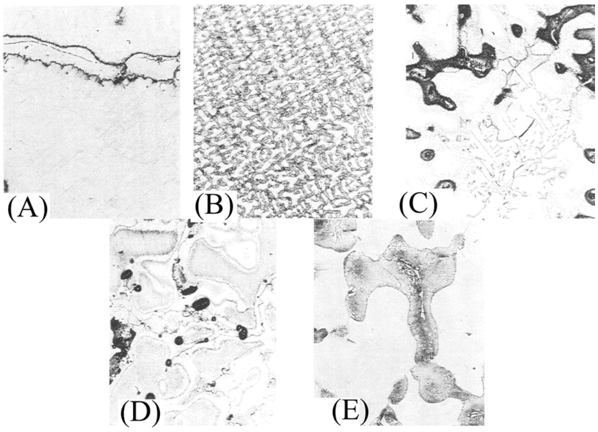

Figure 1. Typical microstructures of A) AM 20, B) AZ 31, C) AS 41, D) AM 60 and E) AZ 91

Slika 1. Karakteristične mikrostrukture A) AM 20, B) AZ 31, C) AS 41, D) AM 60 and E) AZ 91

3. Results and Discussion

3.1. Influence of aluminium content on FBU formation

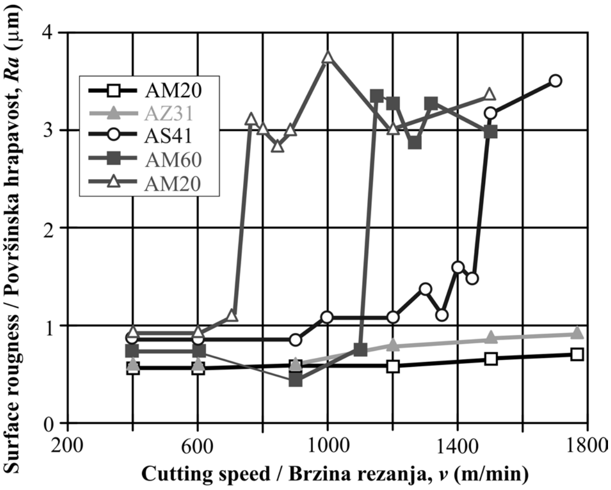

Figure 2. The variation of surface roughness (*Ra*) versus cutting speed (*v*) for five magnesium alloys

Slika 2. Varijacija površinske hrapavosti (*Ra*) nasuprot brzina rezanja (*v*) za četiri magnezijeve legure

Figure 2 shows the effect of cutting speed variations on the average surface roughness for the five machined workpiece materials. These curves are seen to increase sharply when FBU s were formed on tool inserts, indicating marked impairments of surface finish. Associated with the deterioration of surface finish, all tool force components were observed to rise sharply to much higher values with a generation of shorter, more tightly curled chips (like fines) which may represent a higher fire hazard. It is evident that the critical cutting speed (the minimum cutting speed when the FBU is formed) required to form a FBU was much lower for the AZ91 than for the AM60 and especially for the AS41 alloy.

When the AM20 and AZ31 alloys, which both have the low aluminium content, 2 and 3 wt % respectively, were cut, the values of surface roughness were very low at all examined cutting speeds. These resu1ts indicate that no FBU was formed during machining. A slight increase of the surface roughness of the AM20 and AZ31 specimens at high cutting speeds was caused from instabilities within the cutting system, mainly due to spindle vibrations of the machine tool. The effect of the aluminium content on the critical cutting speed is shown in Figure 3. From this figure it is apparent that the critical cutting speed increases with decreasing aluminium content.

3.2. Influence of microstructure on machinability of magnesium alloys

As has been mentioned previously, aluminium is the main element in the examined commercial cast magnesium alloys, which shows a decrease of solubility in the solid state. The high aluminium content of AZ91 alloy causes an appreciable precipitation of β-phase, $Mg_{17}Al_{12}$.

The fact that the amount of intermetallic β-phase decreases with decreasing aluminium content in magnesium alloys may be verified by optical micrography, as well as by solidification curves of such alloys.

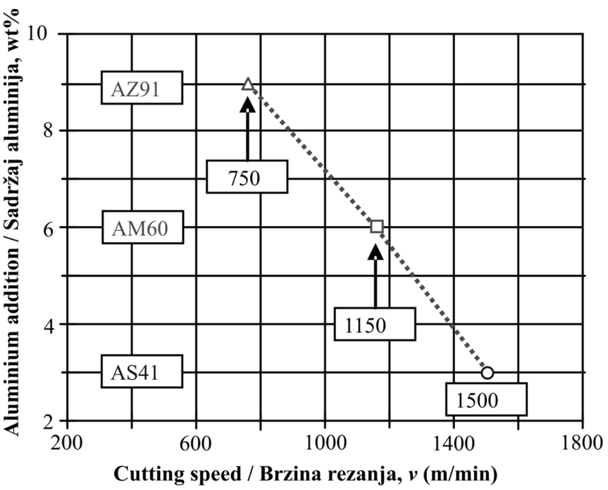

Figure 3. Effect of aluminium content on critical cutting speed (formation of FBU)

Slika 3. Utjecaj sadržaja aluminija na kritičnu brzinu rezanja (formiranje FBU)

3.3. Influence of MnAl particles

Manganese in small amounts is added to magnesium alloys to increase corrosion resistance. One important effect of manganese is that it combines with aluminium to form insoluble intermetallic particles in magnesium matrix. In all commercial cast magnesium alloys some MnAl compounds may be present. The measurements of microhardness of characteristic phases, referred in Table 3, demonstrate that MnAl particles have very high microhardness. Obviously, phases of this kind act like abrasives in an otherwise soft matrix. The experimental studies have shown that presence of MnAl hard particles in magnesium alloys may have a detrimental effect on machinability. Figure 4 shows a damage of the machined surface caused by MnAl hard particles which have been moved by the cutting edge and thus made grooves. In most of cutting tests where the FBU appeared, small sparks or flashes could be seen during the cutting operation, which contribute to a higher fire hazard. In the authors' opinion these sparks are generated as a consequence of temporary and local heat generation caused by friction between the very hard MnAl particles and the cutting edge and/or the workpiece.

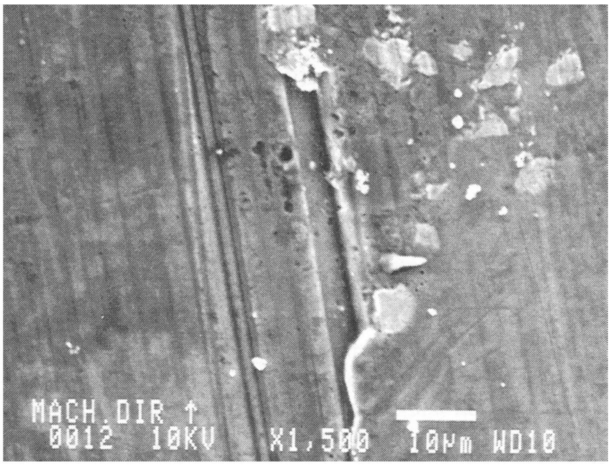

Figure 4. Damage of the machined surface caused by MnAl hard particles which have been moved by the cutting edge and thus made grooves

Slika 4. Oštećenje obrađene površine uzrokovano tvrdim MnAl partiklima koji su se pomaknuli oštricom alata i tako stvorili kanale

Tool inserts used in machining magnesium alloys were examined with scanning electron microscope. Energy disperative analyses have revealed a high concentration of manganese along cutting edges of tool inserts. It has been observed that a protective built-up layer may be formed on the rake face of the tool when the AZ91-F alloy was cut at lower cutting speeds (600 m/min). One of the main characteristics of the layer is that it provides the generation of very law tool forces and better surface finish with negligible tool vibrations.

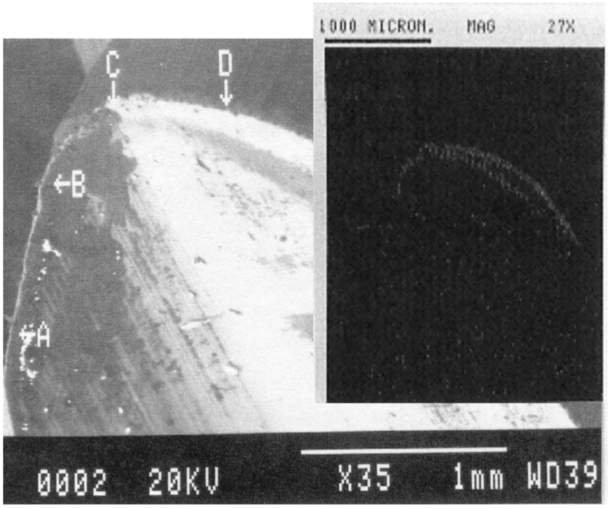

Figure 5. Manganese along cutting edges of tool

Slika 5. Mangan uzduž oštrice alata

Energy disperative analysis carried out on this layer also showed an increased concentration of manganese, see Figure 5. These findings revealed a close similarity between MnAl particles in magnesium alloys with MnS inclusions in free-cutting materials. Manganese sulphide inclusions are known to deposit as layers on the chip-tool interfaces. The formation of the built-up layer was suggested as one of the most beneficial mechanisms for reduction of tool wear and improving the surface roughness of the machined workpiece.

It has been reported that manganese has a high affinity to the cutting tool materials, especially with cemented carbides and titan nitrides [8]. But the precise mechanism by which manganese acts towords the cutting tool is complex and not completely understood.

3.4. Influence of porosity

The adverse effect of porosity on the FBU formation can be seen in the comparison of cutting test results obtained when the AM20 alloy was machined. A visual inspection of the workpiece revealed surface areas with several cracks and pores at one end of the cylindrical surface. No FBU was formed on the non porous area of the workpiece surface at all examined cutting speeds. But it was detected on the small porous area at cutting speeds > 800 m/min.

When defects such as pores and cracks are present in the workpiece a large number of MnAl particles are usually found incorporated around them. A similar phenomenon has been found in grey iron castings where MnS particles were found around pores [6]. Figure 6 shows a scanning electron micrograph of the machined surface of the AZ91-F magnesium alloy generated at cutting speed 900 m/min. It can be seen that the surface contains pores and MnAl particles. These particles have been moved by the cutting edge and thus made straight grooves parallel to direction of relative work-tool motion.

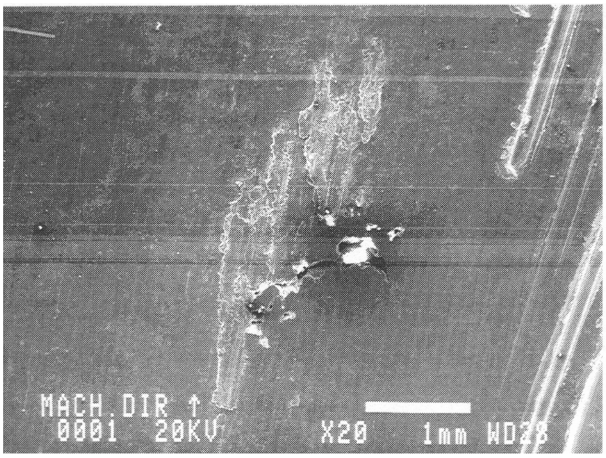

Figure 6. Porosity found in magnesium alloy AZ91

Slika 6. Porozitet pronađen u magnezijevoj leguri AZ91

In order to study the effects of the macropores on the FBU formation, two special interrupted tests have been carried out within a cutting speed range when the FBU is generated. During these tests no FBU was observed. This was explained as the consequence of an absence of highly concentrated MnAl particles near the artificially made grooves in the workpiece. These tests indicate an important role of MnAl particles in the FBU formation.

4. Conclusions

The most significant difference in the machining characteristics of the examined commercial magnesium alloys is related to the FBU formation. It was observed that the presence and amount of intermetallic β-phase ($Mg_{17}Al_{12}$) in magnesium matrix is responsible for the difference in the tendency for FBU formation.

The machining tests which were carried out on the AS41, AM60 and AZ91-F and AZ91-T6 magnesium alloys showed that the FBU was formed at certain "critical" cutting speeds. The microstructure of these alloys showed an appreciable precipitation of β-phase.

The presence of defects such as cracks and pores in the workpiece promote the formation of the FBU.

Since the softening rate of workpiece material depends on the amount of β-phase in the magnesium matrix and cutting temperature, the critical cutting speed will become lower with an increase in the amount of β-phase.

Acknowledgement

The work presented in this report is a part of a larger effort at the Production Engineering for research and development of processes and equipment for the machining of light alloys. The authors are indebted to thank the Norsk Hydro Magnesium and the Nordic Fund for Technology and Industrial Development for financial support of these investigations.

REFERENCES

[1] TOMAC, N.; TØNNESSEN, K.: *Formation of Flank Build-up in Cutting Magnesium Alloys*, Annals of the CIRP, (1991), Vol. 41/1: 98-42.

[2] TOMAC, N.; TØNNESSEN, K.; RASCH, F. O.; MIKAC, T.: *A Study of Factors that Affect the Build-Up Material Formation*, AMST'05, Udine, Italy, (2005): 183-192.

[3] EMLEY, E. F.: *Principles of magnesium Technology*, London, 1966.

[4] PALMER, I. J.: *Metallurgy of the Light Metals*, London, 1989.

[5] TRENT, E. M.: *Metal Cutting, Butterworths*, 1984

[6] *Metals Hanodbok*, Casting, 9-th Edition, Volume 14, 1989, pp. 296–307.

[7] STEPHENSON, D. A.: *Agapiou*, Metal Cutting Theory and Practice, 2006, 670-692.