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Subject review

# Formation of Built-Up Layer on the Tool in Turning Operation of Magnesium Alloys

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**Abstract:** The present work highlights some factors which affect formation of a protective built-up layer (BUL) on the rake face of the cutting tool when cutting magnesium alloys. This work suggests that BUL can positively affect tool life, surface roughness, cutting speed and tool forces. The BUL is formed in cutting magnesium alloys with the PCD tool inserts at cutting speed range from 500 to 2500 m/min and at the carbide tool inserts at lower cutting speed range around 550 m/min. It has been found that deposit layers primarily have similar chemical composition as MnAl inclusions which are incorporated in the structure of the examined AZ91 magnesium alloys.

**Keywords:** built-up layer; machining; magnesium

## 1 INTRODUCTION

It is well known that a protective built-up layer (BUL) is formed on the face surface and/or flank face of the cutting tool when cutting "free machining alloys". A number of machining tests have demonstrated that this layer formation can allow the use of higher cutting speed, produce longer tool life, improve surface finish, reduce tool forces and power consumption. All these machining characteristics may result in a reduction of the machining cost by increasing productivity or eliminating finish machining operations. Therefore, it is essential to understand the effects of built-up layers and their role in improvement of machining properties.

It has been found that deposit layers primarily have the same chemical composition as inclusions which are incorporated in the structure of the work material [1]. These inclusions, which are favourable for the BUL generation, are formed when additives, commonly called free machining additives, such as sulphur, selenium, tellurium, lead and bismuth are added to the work material. The best known, and most widely used, free machining additive is sulphur. When sulphur is added to alloys with a sufficient amount of manganese, the sulphur will combine with manganese to form manganese sulphide (MnS). Manganese sulphide is known to soften rapidly at higher temperatures maintaining hardness less than the steel matrix. It was noted that manganese sulphide has a high affinity to the tool, especially with titanium compounds. The precise mechanism by which MnS inclusions are deposited on the tool surfaces is not understood completely. Buckley [2] has indicated that sulphur is extremely active in inhibiting metal to metal adhesion, even at very high loads. Thus, sulphur acts as an inherent lubricant to reduce friction which in turn reduces shear resistance.

The presence of MnS layers at the tool chip interface produces a reduction in friction and apparent temperature, and consequently diminishes the thermally activated tool wear. MnS seems to act as a lubricating layer and barrier to the diffusion type of wear, which results in an increase of the tool life.

The experimental studies demonstrated that the inclusions, which represent elastic and plastic heterogeneities in the matrix of the alloy, are primarily responsible for the generation of the shear concentration when the alloy is subjected to large plastic strains [1]. In other words, inclusions act as "stress risers" in the primary cutting zone and initiate cracks which lead to fractures in chips, which in turn are more readily broken into small fragments. A number of chip fractography studies revealed that the chip fractures occur only at the specific regions where the free machining inclusions are highly concentrated [2]. Apart from increased rate of metal removal, longer tool life and beneficial breakable chips, the surface finish of the machined part may be also improved. The deposited layers preclude the formation of the built-up edge that degrades the surface finish. Thus, the generated surface roughness is primarily dependent on the geometry and quality of the tool edge, machining conditions and the machine tool, when machining free cutting alloys.

When selenium and tellurium are added to alloys they combine with manganese to form MnSe or MnTe, which may be completely dissolved in MnS or attached to MnS inclusions.

Lead and bismuth are the two most frequently used low melting additives and these are usually found in association with the primary inclusions (MnS). It was unambiguously demonstrated that under high speed machining conditions, the cutting temperature will be high enough to soften Pb or Bi inclusions [3]. Like sulphur, lead acts as an inherent lubricant to reduce friction which in turn reduces shear resistance. The net effect of the low melting phase is to produce thinner and smaller chips, a smaller chip-tool contact area, lowering tool forces, reducing tool wear, and improving the surface finish. It was noted, however, that low melting inclusions are only effective in the presence of the primary MnS inclusions [3].

Some protective adhesion layers were found on TiN and AlCrN coatings [3]. Elements from the workpiece materials (Fe, Mn, Al, Si, etc.) were found on worn TiN layers of cutting tool inserts [4]. It was observed a significant improvement in machinability of mild steels during turning operation when cutting was done by applying a magnet with the tool holder [5].

It was found that turning titanium alloy Ti-6Al-4V with WC/Co cutting tools at cutting speeds 30-60 m/min causes adhesion of BUL of workpiece material on top of the rake face wear land [6].

Bilgin observed that, during the machining of the AISI 310 austenitic stainless steel with titanium carbide cutting tools, the effects of the feed rate and cutting depth on the formation of built-up layers were not significant as the effect of the cutting speed. To prevent formation of built-up layer cutting speeds during the machining of the

AISI 310 austenitic stainless steel higher than 100 m/min are necessary [7].

Pereira, A. A. and Boehs L. have found that the high resolution transmission electron microscopy image and the associated selected area electron diffraction pattern indicate that the built-up layer has a polycrystalline structure. It is suggested that based on high resolution transmission electron microscopy and the knowledge of cutting process, dynamic recrystallization took place in the formation of the built-up layer [8].

## 2 EXPERIMENTAL PROCEDURES

The cutting tests were conducted using a 22 kW OKUMA centre lathe, with a continuously variable spindle speed. Tool forces were constantly measured with Kistler 9257 A, a three component piezoelectric crystal dynamometer. The tests were conducted as turning on bars of 500 mm length and 150 mm diameter, and the tooling was: Cemented carbide inserts, carbide grade ISO KI0 (HIO), ISO-standard TCGX 16T308- Al, ($\gamma$ = 20°, $\alpha$ = 7°), c1amped in a T-MAX U STTCL 2525 M16 tool holder and diamond tipped, carbide based inserts, ISO standard TCMW 16T304L-H CDI0, clamped in a T-MAX U STTCL 2525 M16 tool holder. A CD 10 insert consists of a layer of polycrystalline diamond (PCD) on a cemented carbide substrate formed as an integral blank, and brazed onto cemented carbide inserts.

The turning tests were carried out to determine the influence of cutting speed on the formation of built-up layer. The depth of cut 0.4 mm and the feed per revolution 0.1 mm were held constant, as standardised by CIRP for finish cutting tests. The investigation was generally performed as "short-time" cutting tests where each cutting edge was used for just one single pass over the workpiece. Two Mg-Al-Zn alloys produced at Norsk Hydro- Magnesium Division were used as workpiece materials. The chemical composition and hardness values are shown in Tab. 1.

The first alloy is a high purity casting alloy that has very low levels of iron, copper and nickel. This alloy is far more resistant to corrosion, and is used in a number of automotive applications, such as clutch and transmission housings, wheels, headlight brackets, valve covers and body panels. Another alloy is an experimental AZ91 alloy with relatively high percentage of manganese.

**Table 1** Chemical composition, wt-% of the workpiece materials

| ALLOY | %Al | %Mn | %Zn | %Si | %Fe | HV50 |
|---|---|---|---|---|---|---|
| 1. AZ91 | 9.5 | 0.17 | 0.5 | 0.05 | 0.004 | 65.8 |
| 2. AZ91 | 8.8 | 0.22 | 0.63 | 0.011 | 0.005 | 71.6 |

Because manganese seems to have a high attraction to the cutting tool, two similar AZ91 alloys with different manganese content were used. The structural characteristics of AZ91 magnesium alloys have been studied using X-ray diffraction and scanning electron microscopy.

## 3 RESULTS AND DISCUSSION

Manganese in small amounts is added to magnesium alloys to increase corrosion resistance and to remove iron and certain other impurities into relatively harmless intermetallic compounds, but has little effect on mechanical properties. An intermetallic compound is formed in the melt and, being heavy, sinks to the bottom of the casting thus reducing the effective iron content.

When cutting magnesium alloys with HM tool inserts there is a cutting speed range where the surface roughness obtained has the minimum Ra value and minimum tool forces with very low vibrations are recorded. In this cutting speed range a favourable built-up layer was formed on the face surface of tool, see Fig. 4.

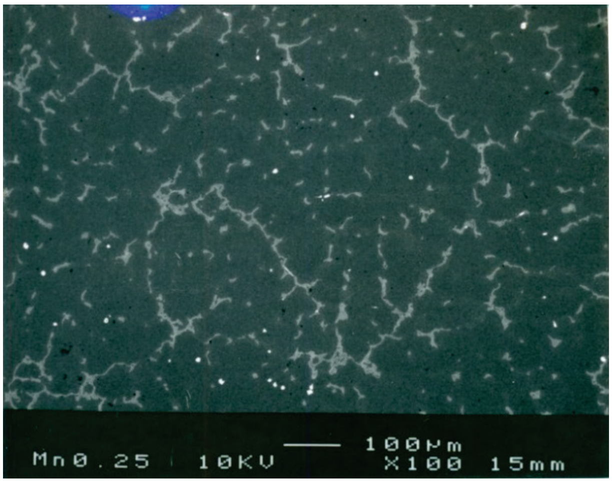
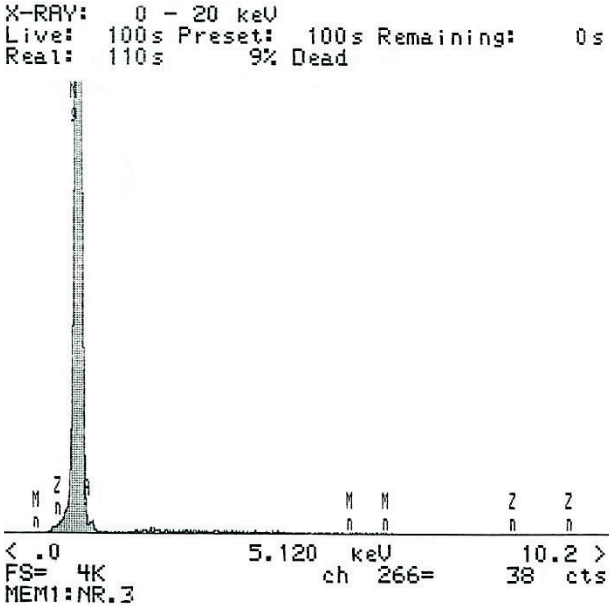


**Figure 1** Typical microstructure of the AZ 91 magnesium alloy



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X-RAY:   0 - 20 keV
Live:  100s Preset:  100s Remaining:    0s
Real:  110s       9% Dead
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< .0              5.120  keV           10.2 >
FS=  4K                 ch  266=        38  cts
MEM1:NR.3
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**Figure 2** Results of the energy disperative analysis carried out on the AZ 91 magnesium alloy

The tool forces in the BUL cutting speed range are very low and remain constant during the actual cutting length. It seems that the layer acts as a lubricant between the tool and chip. It also contributes to the protection of the tool from wear. A similar BUL can be detected on the polycrystalline diamond (PCD) too1 inserts. Fig. 5 illustrates the variation of arithmetic average surface roughness (*Ra*) with cutting speed (*v*) for PCD and cemented carbide tools.

When the workpiece material was cut with cemented carbide at cutting speeds over 950 m/min, a drastic deterioration of surface finish resulted. This was caused by the flank build-up (FBU), which grew on the flank surfaces and came in contact with the machined surface. This generated a number of grove like irregularities on the machined surface and also caused diameter deviations.

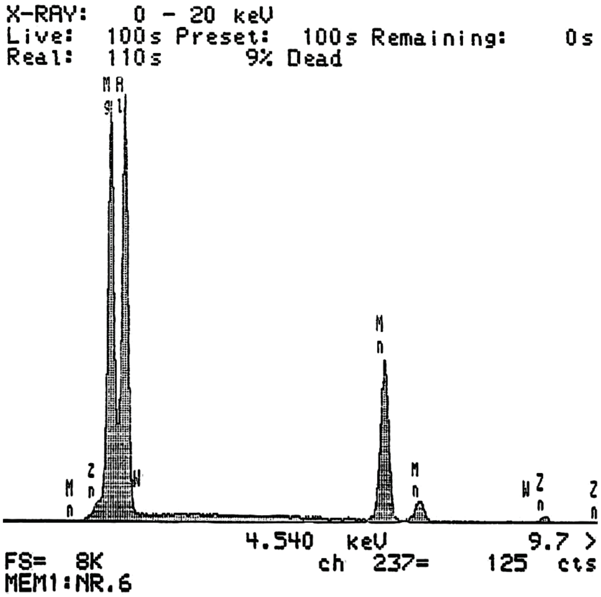

**Figure 3** Results of the energy disperative analysis carried out on a MnAl particle in a magnesium alloy

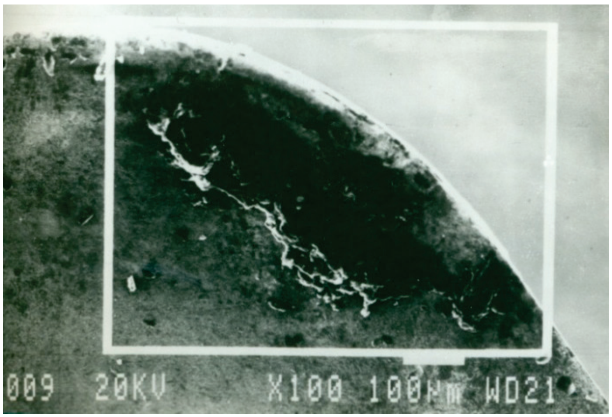

**Figure 4** Scanning electron micrograph of cutting tool with the BUL on the rake face, at cutting speed 550 m/min

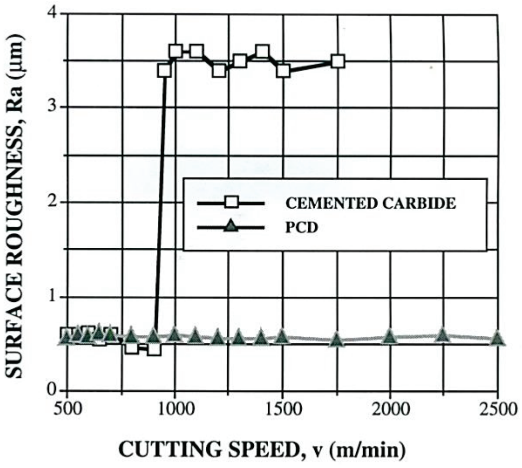

**Figure 5** Comparison between surface roughness versus cutting speed in machining with carbide and PCD tools

When cutting magnesium alloys with PCD tool inserts at high cutting speeds (500-2500 m/min) the composition of workpiece material could be detected as a layer on the tool rake face.

Fig. 6 shows a PCD tool insert after cutting for 30 min showing the material layer on the rake face. This build-up layer was examined in JOEL electron microscope with a quantitative energy disperative X-ray analysing system. Energy disperative X-ray (EDX) rnicroanalysing was used to estimate the microcontent of the BUL on a PCD tool. The regions chosen for analysis were 1 to 0.5 mm from the cutting edge. The manganese content in the BUL was found to increase reaching a value of about 20%, in comparison to the workpiece material where the manganese content is 0.17 %.

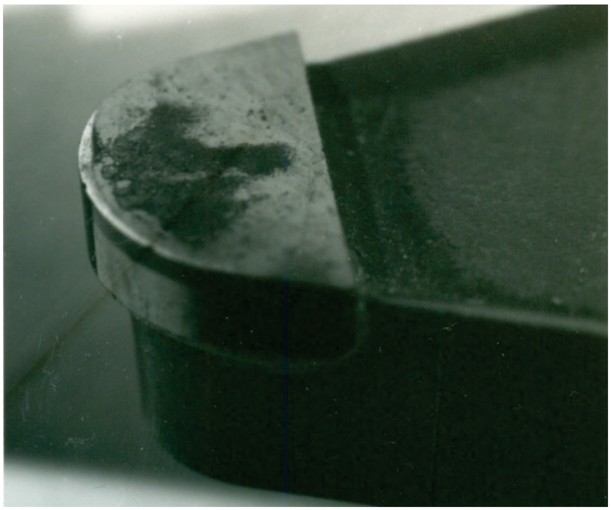

**Figure 6** PCD tool insert after cutting for 30 min showing material layer on rake face of tool

Tab. 2 shows the atomic percentage of metallic components in the BUL obtained from the SEM-EDX.

**Table 2** Analysed chemical composition of BUL area

| Element | Mn | Al | Ti | Mg | Co | other |
|---|---|---|---|---|---|---|
| % | 19.7 | 30.3 | 5.28 | 20.41 | 14.41 | 9.27 |

Fig. 7 shows the results of the energy disperative analysis carried out on the BUL. The causes of the formation of the BUL and the familiar phenomena built-up edge (BUE) are not fully understood.

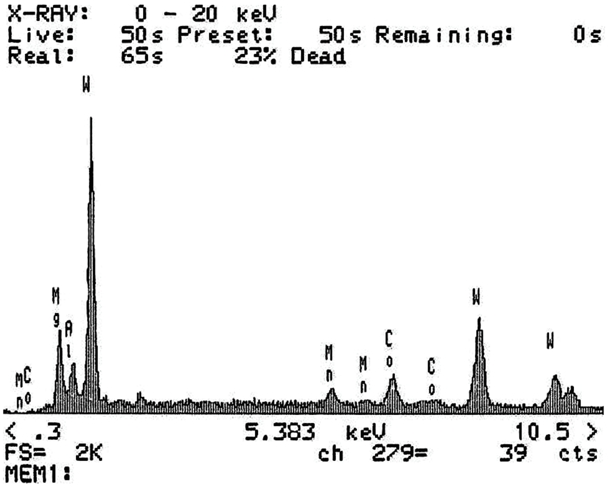

**Figure 7** Results of the energy disperative analysis carried out on the build-up layer

Microscopic examinations of the magnesium alloys revealed the presence of hard MnAl particles in their microstructures. Manganese in small amounts is added to magnesium alloys to increase corrosion resistance and to remove iron and certain other impurities into relatively harmless intermetallic compounds.

Manganese in magnesium alloys, in the presence of aluminium combines with it to form the MnAl compounds. Analysed chemical composition of the BUL area proves that the MnAl compounds have a high affinity to the tool materials. Microhardness tests values as high as 150 HV were observed in the BUL of an AZ 9l magnesium alloy compared with 70 HV in the workpiece itself.

The formation of BUL in machining of free cutting alloys is completely similar to the formation of the BUL in machining of magnesium alloys. This layer formation exhibits several beneficial effects:

- Protects the tool from wear which may yield an increased metal removal rate at a given tool life
- Reduces the cutting energy required due to a smaller chip/tool contact area and consequently cutting and tool temperature reduction
- Enables the use of faster cutting speeds and feeds
- Produces better surface finish.

## 4 CONCLUSION

The protective built-up layer (BUL) is formed in cutting magnesium alloys with the PCD tool inserts at cutting speed range from 500 to 2500 m/min and at the carbide tool inserts at lower cutting speed range around 550 m/min.

The BUL primarily has a similar chemical composition as MnAl inclusions which are incorporated in the structure of the examined AZ91 magnesium alloys.

The formation of BUL in machining of free cutting alloys is completely similar to the formation of the BUL in machining of magnesium alloys.

The tool forces in the BUL cutting speed range are very low and remain constant during the actual cutting length. It seems that the layer acts as a lubricant between the tool and chip. It also contributes to the protection of the tool from wear.

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