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ISSN 0543-5846
METABK 51(1) 34-38 (2012)
UDC – UDK 669.715:621.96:621.773:620.18=111

THE MICROSTRUCTURE INFLUENCE ON THE CHIP FORMATION PROCESS OF AL-CU ALLOY CAST CONVENTIONALLY AND IN SEMI SOLID STATE

Recevied – Prispjelo: 2011-01-20
Acctepted – Prihvaćeno: 2011-03-25
Original Scientific Paper – Izvorni znanstveni rad

For many metal alloys, the process of metal cutting is accompanied by extensive plastic deformation and fracture. To study this process, quick stop sectional samples of hypoeutectic Al-Cu alloy chip formation, either as conventionally cast alloy or as "semi solid metal" are used. The type of chip formation is classified according to crack formation mechanism and propagation. During cutting, in all specimens used, quasi-continuous chips with built-up edge (BUE) are obtained. The formation of BUE is undesirable since it is a highly deformed body with a semi stable top which periodically breaks away giving rise to poor workpiece surface quality.

Key words: aluminium alloys, cutting process, chip formation, microstructure, semi solid metal

Utjecaj mikrostrukture na proces nastajanja strugotine za konvencionalnu i polutekuću lijevanu Al-Cu leguru. Za mnoge metalne legure, proces rezanja je praćen intenzivnom plastičnom deformacijom i lomom. Za istraživanje tog procesa u radu je korištena metoda brzog zaustavljanja procesa rezanja. Materijal uzorka je podeutektička Al-Cu legura, lijevana konvencionalno i kao „polu čvrsti metal" (semi solid metal-SSM). Vrsta strugotine koja je obrazovana klasificirana je prema mehanizmu nastajanja i širenja pukotina. Tokom rezanja, u svim uzorcima nastajala je, kvazi-kontinuirano strugotina sa naslagama (BUE). Stvaranje BUE je nepoželjan proces, jer je to jako deformirani volumen sa polu stabilnim oblikom, koji povremeno raste i odvaja se, što dovodi do lošeg kvaliteta obrađene površine.

Ključne riječi: legure aluminija, proces rezanja, nastajanje strugotine, mikrostruktura, polu čvrsti metal

INTRODUCTION

Aluminium-copper alloys offer both high strength and excellent ductility, where those values are approaching some grades of ductile iron and they are significantly higher than these of Al-Si-Mg family. They have a number of potential applications in automotive industry to reduce vehicle weight, including automotive suspension knuckles, vehicle control arms, and differential carrier parts, aerospace and military castings [1]. However, the alloy is very difficult to cast because of its tendency for hot tearing. Hot tearing is a severe casting defect that generally occurs when casting solidifies and contracts under conditions that hinder the free contraction of casting parts. To overcome this problem, a semi-solid gravity casting can be used. The material produced by this technology is referred to as "Semi Solid Metal" (SSM). Rheocast produced semi-solid metal which reduces hot tearing tendency since the slurry possesses fine-grained and non-dendritic structure. In addition, partially solidified metals result in less solidification contraction [2, 3]. The SSM characteristics and potential benefits are presented in Table 1 [4].

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Generally, machining by material removal process is the most common process in the production of machine parts. Cutting process is suitable for machining of almost all materials (ferrous and non-ferrous, soft and hard, ductile and brittle, etc.). Machinability of materials is one very important characteristic of materials and expresses capability of machining with the most economic methods [5, 6].

The characteristics of machine parts (as duration, fatigue, wear, etc.) depend not only on the construction shape, but also on surface layer state after metal cutting. The parameters and phenomena, like state and quality of surface layer, cutting temperature, cutting forces, etc., are strictly connected with chip geometry and shape [6].

The chip forming process theoretically might be explained by different models. One of the most known is Brix model [7], which represent chip forming like successive lamellas forming process, Figure 1. Although, this model is very sophisticated, it only takes into count behavior from *post factum* observation like the velocities, the cutting forces and the geometry around the tool and ignores material microstructure [8]. It was the reason that in this study an attempt has been made to correlate the chip formation process and the material microstructure of Al-Cu alloys.

Table 1 **Characteristics of SSM for exploitation [4]**

Characteristics	Potential benefits or applications
Lower heat content than liquid metal	Higher speed of part forming Higher speed continuous casting Lower mold erosion Ferrous part forming Forming of other high-melting point materials Forming of reactive metals
Solid present of time of mould filling	Less shrinkage voids Less feeding required Less macro segregation Fine grain structure
Viscosity higher than in liquid metals, and controllable	Less entrapped mould gases Reduced oxides-improved machinability Less mold attack Improved surface finish Automation New processes
Flow stress lower than for solid metals	Forming of Intricate parts High speed part forming Lower cost part forming High speed forming of continuous shapes New processes
Ability to incorporate other materials	Composites
Ability to separate liquid and solid	Purification

It is known, that the machinability of conventionally cast Al-Cu alloys depends primarily on the shape, size and distribution of the eutectic and Al_2Cu precipitation present in the microstructure [9, 10]. As mentioned before, in "Semi Solid Metal" production of Al-Cu alloy, the microstructure morphology is changed. This change may consequently influence the machinability; therefore, the study of SSM machinability is of great interest.

In this paper, chip root specimens of hypoeutectic Al-Cu alloy obtained by a quick stop method are studied. The main goal is to study the microstructure influence of conventional and semi solid state produced Al-Cu alloy microstructure, on the chip formation process.

The paper is part of continual research program of material composition and microstructure influence on chip formation process at the Faculty of Technical Sciences, Department of Production Engineering and also the subject matter of cooperation with Prince of Songkla University, Faculty of Engineering in Thailand.

MATERIAL AND EXPERIMENTAL PROCEDURE

The influence of microstructure on chip formation process during aluminium alloy cutting (Al-4,4 %Cu-0,17 %Fe), was studied. Two types of specimens were used. The first one was cast conventionally while the second was produced by semi-solid gravity casting (SSM). To produce the SSM specimens, a new technique was used. This novel process uses gas bubbles as the medium to agitate molten metal during initial stages of solidification [2, 3]. The configuration uses porous graphite rod as gas diffuser to provide the fine argon gas bubbles. The diffuser was connected to Argon gas cylinder equipped with gas flow meter, Figure 2. The alloy was melted and then injected with Argon gas through the graphite rod at the temperature of approx. 650 °C for about 10 sec. The slurry was than casted in a mold.

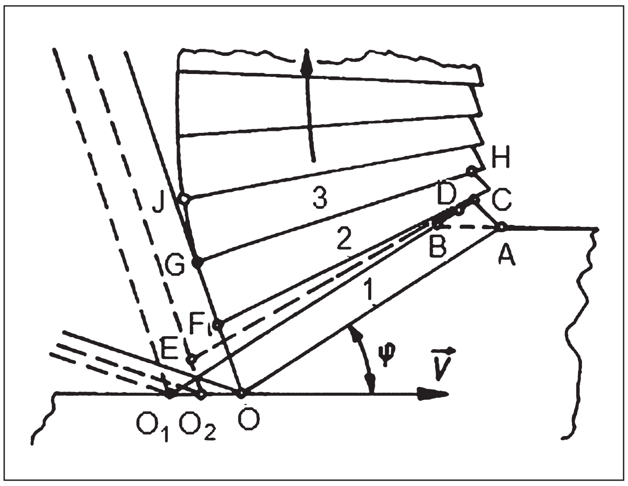

Figure 1 Brix model with lamellas formation during chip forming process [7]

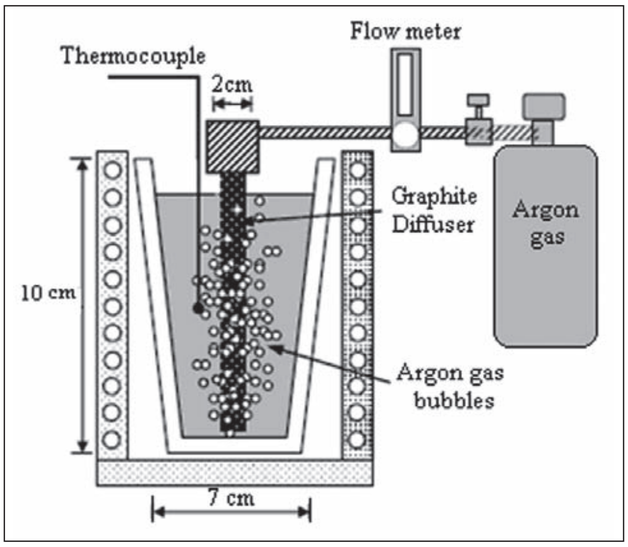

Figure 2 Schematic of the apparatus used in the study (not to scale) [3]

After casting, specimens of dimension 10×10×50 mm were prepared and machined on vertical 12 kW milling machine, by means of a milling head with hard metals inserts. Machining was carried out without cutting liquid. To obtained chip root specimens, quick stop method for freezing of cutting process was used. This method is originally developed by the authors from the Faculty of Technical Sciences, Novi Sad and it can be used in all cutting process technologies [11].

The specimens for microstructure analysis were prepared by standard metallographic technique and were examined on Leitz-Orthoplan light microscope and JEOL JSM6460LV scanning electron microscope equipped with an energy dispersive (EDX) spectrometer, INCA X-sight Oxford Instruments, operated at 20 kV.

RESULTS AND DISCUSSION

The microstructure of conventional casting samples and semi solid metal (SSM) samples are presented in Figures 3 to 6, respectively. In both types of samples, microstructure consists of α solid solution and Al_2Cu phase. However, the grain size and distribution of Al_2Cu are different. Conventional cast samples have coarse α solid solution the grains and precipitation of Al_2Cu particles inside the grain and small Al_2Cu particles in the eutectic (α+Al_2Cu) which is as a thin film along grain boundaries (Figures 3 and 4).

The semi-quantitative chemical analyses of eutectic and Al_2Cu particles are shown in Table 2, from which it can be seen that Al_2Cu phase might be with or without Fe. The microstructure of SSM consists of finer grains of α solid solution and eutectic (α+Al_2Cu) without Al_2Cu precipitation inside grains, Figure 5. The detail of SSM microstructure is shown in Figure 6, while chemical composition is presented in Table 3. The grain refinement was obtained by dendrite braking due to introduced argon gas bubbles during solidification. Furthermore, the amount of eutectic was increased, Figures 5 and 6.

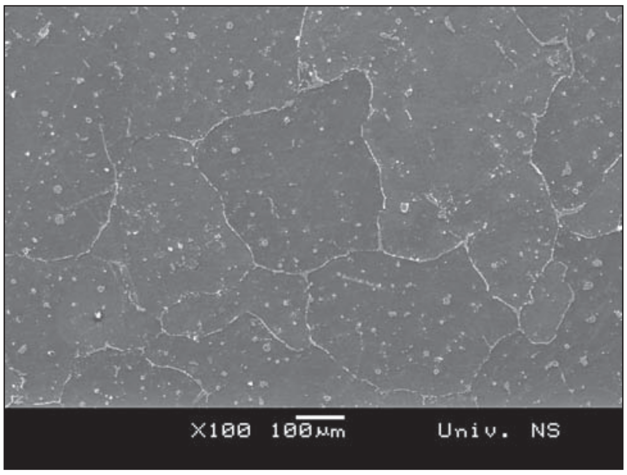

Figure 3 Microstructure of conventionally cast alloy

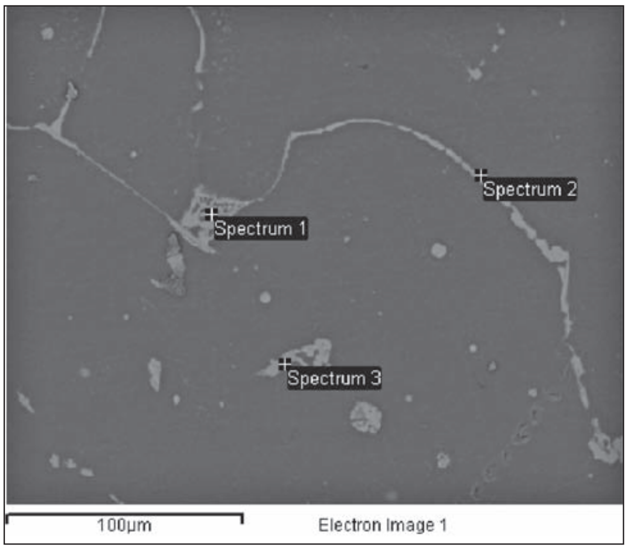

Figure 4 Positions of EDX analyses for conventionally cast alloy

Table 2 **EDX analyses of conventionally cast alloy**

Spectrum	Al	Fe	Ni	Cu	Zn
Spectrum 1	65,04	1,05	0,45	33,46	-
Spectrum 2	89,79	-	-	9,46	0,75
Spectrum 3	54,64	11,33	0,60	33,43	-

Table 3 **EDX analyses of SSM**

Spectrum	Al	Fe	Cu
Spectrum 1	98,69	-	1,31
Spectrum 2	66,68	-	33,32
Spectrum 3	81,60	1,26	17,15

The cross sections of chip root samples obtained during milling are shown in Figures 7 and 8. The cutting conditions were: speed v=27,7 m/min, feed s_1=0,562 mm/tooth and depth of cut 3 mm.

It can be seen that cutting process consists of intensive plastic deformation in primary and secondary cutting zone and fracture. The line of the grains texture is approximately parallel in the whole width of chip, Figures 7 and 8. The angle of grain texture changes according to cutting conditions and material properties. Only in the small area which is in contact with tool surface, the line of grain texture is bended (secondary de-

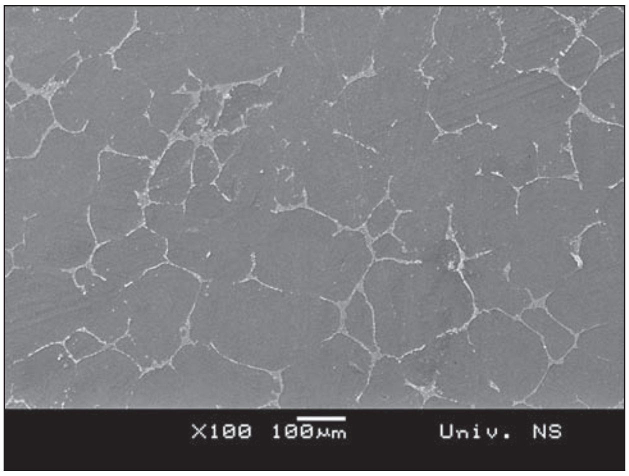

Figure 5 Microstructure of SSM

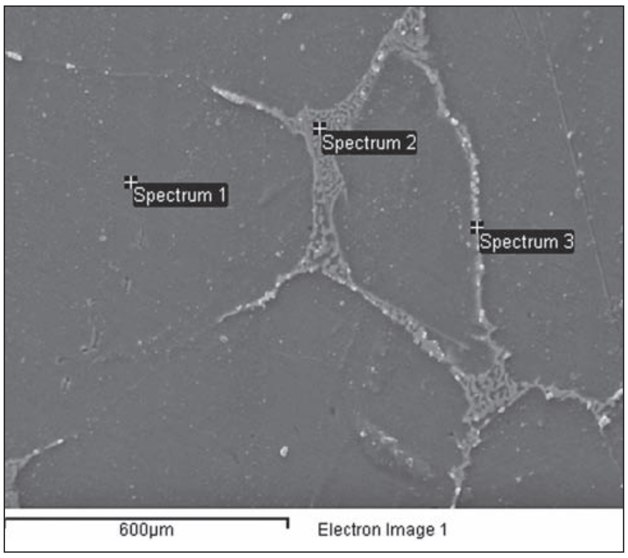

Figure 6 Positions of EDX analyses for SSM

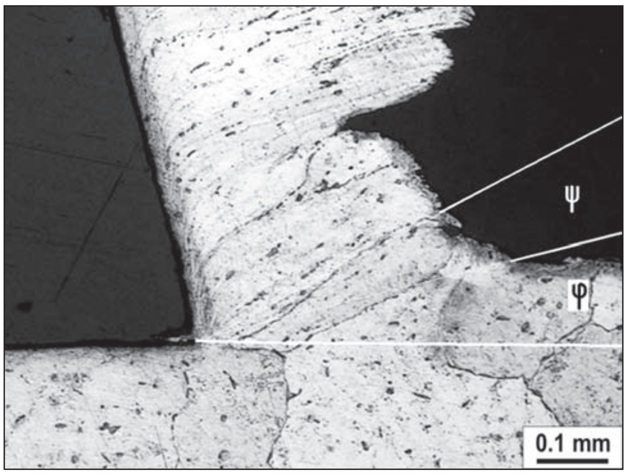

Figure 7 Chip root on conventionally cast alloy

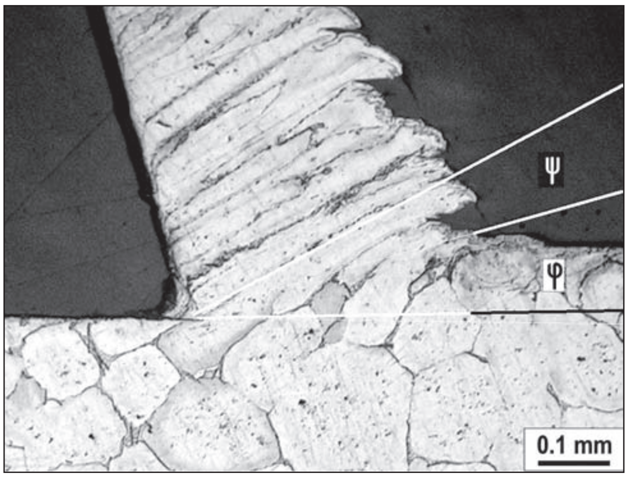

Figure 8 Chip root on SSM

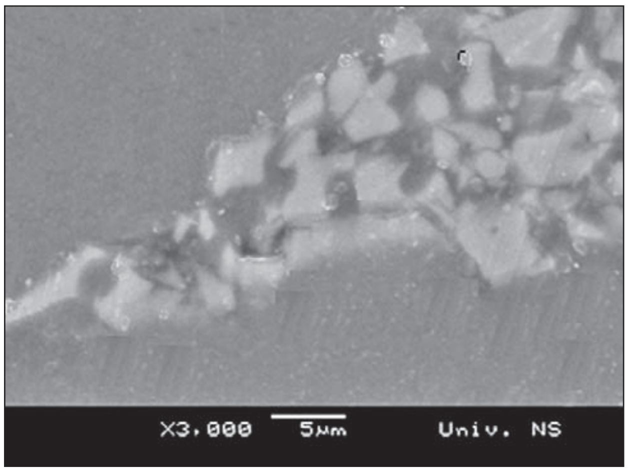

Figure 9 Microvoids in eutectic (SSM)

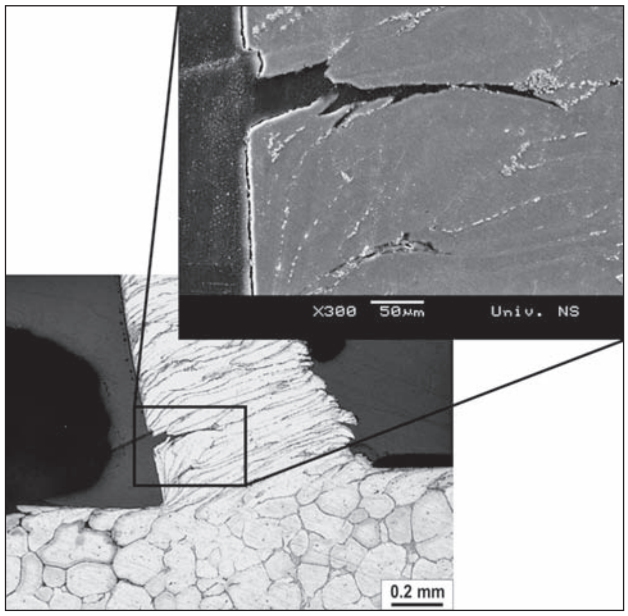

Figure 10 Microcracks appearance trough eutectic in SSM

formation zone). Actually, grain texture bending is resulting from contact friction and pressure of the tool rake surface during chip forming process. The angle of texture ψ is higher than the angle of shear plane φ. The lamellas represented in the Brix model (see Figure 1) are actually deformed grains and they are nearly of equal thickness (see Figures 7 and 8). In all specimens, the chip is quasi-continuous with lamellas and easy breaking. The SSM has smaller grains; consequently the lamellas are thinner than lamellas in conventionally casted alloy where grains are larger. Moreover, in the most cases, lamellas in conventionally alloy are consisted of one grain, while in the case of SSM when grains are smaller, lamella are often made of a few.

The outside of chip is rough (like saw tooth) as the deformation of grains on this surface is not limited and during cutting, the material is squeezed and flows out. The size of “saw tooth” depends on the size of lamellas i.e. on the size of grains; when the grains are smaller, “saw tooth” on the opposite side of the chip are smaller and vice verse.

The presence of the eutectic in microstructure increases the appearance of cracks during the cutting process. Actually, the microvoids are formed on Al_2Cu eutectic particles as they are less deformable than the matrix, Figure 9. Because of this, during shearing, dislocations are required on the interface. These dislocations pile up until their combined energy exceeds the internal energy and then crack or decohesion occurs [11, 12].

The higher amount of the eutectic, the higher number of nucleated voids. Furthermore, coalescence of microvoids leads to micro cracks appearance. This enables easier process of chip formation and breaking, Figure 10.

It can be noticed that besides microstructure refinement by SSM, some argon gas bubbles might be captured in metal. These bubbles generate conditions for appearance of microcracks. Although those microcracks enable easier process of chip forming and braking they might generate the porosity as an undesirable defect in cast.

During machining of all tested samples by cutting conditions used, built up edge (BUE) is continually formed which is typical for aluminium, Figure 11. The identified BUE is semi stable high plastic deformed part of material and it is partially connected with chip and machined surface. The SSM samples have more stable and continual BUE on chip root.

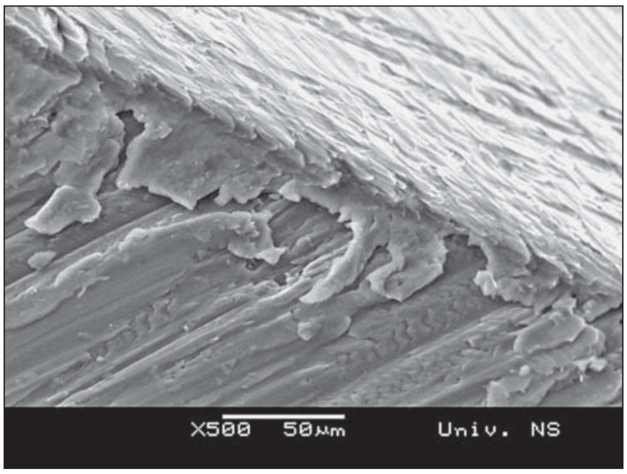

Figure 11 Built up edge on the chip root (conventionally cast specimen)

According to all above stated, it might be concluded that SSM has better machinability than conventionally cast Al-Cu.

CONCLUSIONS

According to results obtained a following conclusion can be suggested:

- During milling, in all specimens used, quasi-continuous chips with built-up edge (BUE) were obtained.
- The chip type depends primarily on the amount and morphology of eutectic in Al-Cu alloy.
- Higher amount of eutectic in SSM stimulates microvoids nucleation and coalescence and further appearance of microcracks. This influences easier machinability of SSM than conventionally cast Al-Cu alloy.
- The surface finish is of poor quality for both types of specimens as the constant BUE is present. Furthermore, in the case of SSM some argon gas bubbles are present on the surface contributing to even lower surface finish quality.

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Note: The English language proofreading was done by Professional lecturer - Sworn Court Translator, Gordana Rašković, Novi Sad, Serbia