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## THERMO-MECHANICAL PROCESSING OF RAPIDLY SOLIDIFIED 5083 ALUMINIUM ALLOY – STRUCTURE AND MECHANICAL PROPERTIES

### OBRÓBKA CIEPLNO-MECHANICZNA SZYBKO KRYSZALIZOWANEGO STOPU 5083 – STRUKTURA I WŁASNOŚCI MECHANICZNE

Aluminium-magnesium 5083 alloy was rapidly solidified by means of melt spinning technique and plastically consolidated during subsequent hot extrusion process. As a result, rods 8 mm in diameter were obtained. Structure of as-extruded material is characterized by ultra-fined grains, which influences on increase of mechanical properties of the material. The strengthening effect was further enhanced by application of thermo-mechanical treatment consist of cold rolling combined with isothermal annealing. As a result, reduction of grain size from ~710 nm to ~270 nm as well as enhancement of yield stress (330 MPa to 420 MPa) and ultimate tensile strength (410 MPa to 460 MPa) were achieved. Based on received results Hall-Petch coefficients ( $\sigma_0$ ,  $k$ ) for 5083 RS material were determined.

*Keywords:* Rapid solidification, Al-Mg alloy, thermo-mechanical treatment

Stop aluminium 5083 został poddany szybkiej krystalizacji z następującą po niej plastyczną konsolidacją w procesie wyciskania na gorąco. Otrzymane pręty o średnicy 8mm posiadały strukturę sub-mikronową dającą w efekcie podniesione własności mechaniczne: granicę plastyczności 330 MPa i wytrzymałość na rozciąganie 410 MPa. Tak otrzymany materiał poddano dodatkowej obróbce cieplno-mechanicznej. W wyniku otrzymano znaczne podniesienie właściwości mechanicznych. W najlepszym przypadku dla ziarna o średniej średnicy 270 nm otrzymano materiał o granicy plastyczności 420 MPa oraz wytrzymałości 460 MPa. Parametry mechaniczne otrzymane dla różnych średnic ziaren pozwoliły na określenie parametrów równania Hall’-Petch’a.

#### 1. Introduction

Aluminium alloys with high specific strength, good ductility and corrosion resistance have found many applications, especially in the transportation industry. In particular, aluminium alloys of 2xxx and 7xxx series represent the great research interest due to favorable combination of strength and ductility. It has been already recognized that aluminium alloys with copper, zinc and magnesium additions benefits from precipitation strengthening, however suffers from low corrosion resistance and poor weldability. On the contrary, aluminium alloys of 5xxx series are known to be weldable and corrosion resistant, however due to lack of the precipitation strengthening mechanism, poses only moderate strength. It is known that susceptibility of Al-Mg system to precipitation hardening is negligible, thus considering significant improvement of mechanical properties of Al-Mg alloys research interest should be focused on hardening mechanisms based on: solid solution, deformation and grain size strengthening [1].

Recently, significant efforts have been made to apply novel processing techniques that can effectively enhance strength of Al-Mg alloys by the structure refinement. Effective re-

finement of the grain size can be achieved on the way of new processing techniques such as severe plastic deformation (SPD) [2] or rapid solidification [3, 4] followed by the sintering or plastic consolidation processes. SPD techniques are very efficient for the structure refinement to the range of nanometers but dimensions of as-processed materials are still too small for industrial applications. Contrary, rapid solidification combined with the conventional processing such as hot extrusion, provides an effective way for wrought alloys production. Increased mechanical properties [5, 6], thermal stability [7] and corrosion resistance can be achieved due to grain size and intermetallic phase’s refinement.

It has been already recognized that in the case of 5083 aluminium alloy effective enhancement of mechanical properties can be obtained by grain size refinement. It has been shown that the grain size of 5083 aluminium alloy processed by industrial routes can be reduced to several micrometers [8, 9]. Our early research works in 5083 alloy [6] suggested that rapid solidification combined with hot extrusion process allow to obtain grain size below 1  $\mu\text{m}$ . Based on this results an attempt for further reduction of grain size by thermo-mechanical treatment has been made.

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In this study we are focused on the effect of thermo-mechanical treatment on the structure and mechanical properties of 5083RS alloy.

## 2. Experimental

The commercial alloy AA5083 with composition given in Table 1 was rapidly solidified by means of melt spinning technique. Molten alloy was cast onto copper wheel, rotating with circumferential velocity of 20 m/s. Received ribbons with dimensions of 50  $\mu\text{m}$  thickness and 2 to 3 mm width were cut to small pieces and preliminary cold compacted under a pressure of 200 MPa to produce cylindrical billets. The as-compressed billets were then degassed and hot extruded at 400°C with cross-section reduction ratio of  $\lambda = 25$ . As a result, rods of 8 mm in diameter were obtained. Further processing of as-extruded RS material included various combinations of thermo-mechanical treatment consist of cold rolling followed by isothermal annealing. One and two-step procedures were applied with the total deformation that corresponds to the true strain of 0.7 and 1.4, respectively. After each deformation step, isothermal annealing at 300°C for 3h was performed. All combinations of parameters used in experiment are shown in Figure 1. In addition to processed samples fully recrystallized 5083RS alloy was studied as well.

TABLE 1  
Chemical composition of AA5083 alloy (wt.%)

Mg	Mn	Si	Zn	Fe	Cr	Ti	Al
4.00-4.90	0.40-0.10	max. 0.40	max. 0.25	max. 0.40	max. 0.25	max. 0.15	balance

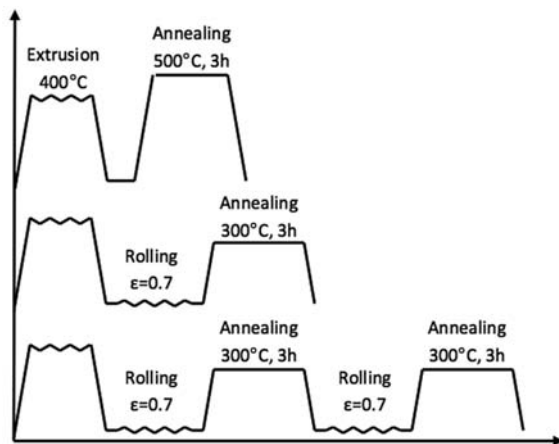


Fig. 1. Schematic of thermo-mechanical procedures: extrusion followed by annealing at 500°C for 3h (upper scheme), extrusion followed by 1 step procedure of deformation and annealing (upper scheme), extrusion followed by 2 step procedure of deformation and annealing (lower scheme)

Due to sub-micron grain size transmission electron microscopy was used for structural investigations. Electron transparent foils suitable for TEM observations were obtained by mechanical grinding to the thickness of  $\sim 50 \mu\text{m}$  followed by electrochemical thinning by using twin-jet system and standard Struers procedures. Structural observations were carried out using a Hitachi SU-70 scanning electron microscopy equipped

with transmission electrons detector. Equivalent grain size diameter was estimated from at least 10 SEM images and an average grain size value was determined. It is important to mention that grain size measurements cover both grains and sub-grains because diffraction contrast does not allow to distinguish between low and high angle boundaries.

Mechanical tests were performed at room temperature with a constant cross-head velocity corresponding to an initial strain rate of  $10^{-2}\text{s}^{-1}$ . For each type of material at least three specimens were tested. Based on received results the 0.2% proof strength ( $\sigma_{0.2}$ ), ultimate tensile strength ( $\sigma_{UTS}$ ) and elongation to failure ( $\epsilon_f$ ) were determined.

## 3. Results

Typical structure of as-extruded 5083RS alloy at cross-section parallel to extrusion direction is shown in Figure 2. Equiaxed grains with relatively low dislocation density are formed during extrusion as a result of dynamic recrystallization processes. The average grain size diameter determined for as extruded material is  $\sim 710 \text{ nm}$ . Black dots visible in the structure (Fig. 2) were found to be intermetallic phases containing Fe, Cr, Ti. Chemical analysis of these particles can be found elsewhere [6]. Application of rolling process leads to the substantial increase of dislocation density as it is shown in Figure 3. However, isothermal annealing at 300°C leads to the activation of recrystallization process and redistribution of dislocations which in turns result in formation of new grains or subgrains in the structure.

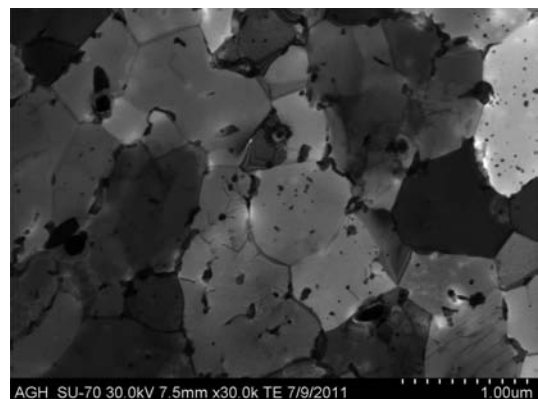


Fig. 2. STEM image of as-extruded 5083RS alloy

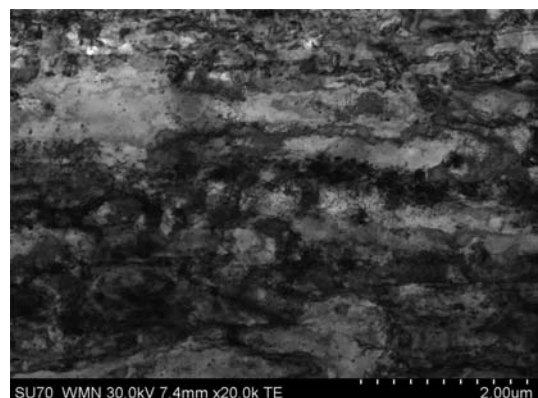


Fig. 3. STEM image of as-extruded 5083RS alloy subjected to the cold rolling (deformation correspond to the 0.7 of true strain)

Effective reduction of the grain size for materials after thermo-mechanical treatment is noticeable as it is shown in Figure 4b-4c. An average grain size decreases from initial value of  $\sim 710$  nm for as extruded material to  $\sim 360$  nm and  $\sim 270$  nm for one and two steps of thermo-mechanical treatment, respectively. In order to completely recrystallize as-extruded material annealing process at  $500^\circ\text{C}$  for 3h was performed (Fig. 4d). Grain structure as well as the intermetallic phase's distribution was revealed by contrast imaging using BSE (Back Scattered Electrons) detector. It can be seen that grains are characterized by irregular shape with an average grain diameter of  $\sim 100$   $\mu\text{m}$  (Fig. 4d). It is considered that structure coarsening observed for that material is governed by the abnormal grains growth. Moreover, substantial growth of the intermetallic phases to the range of several micrometers is also noticeable.

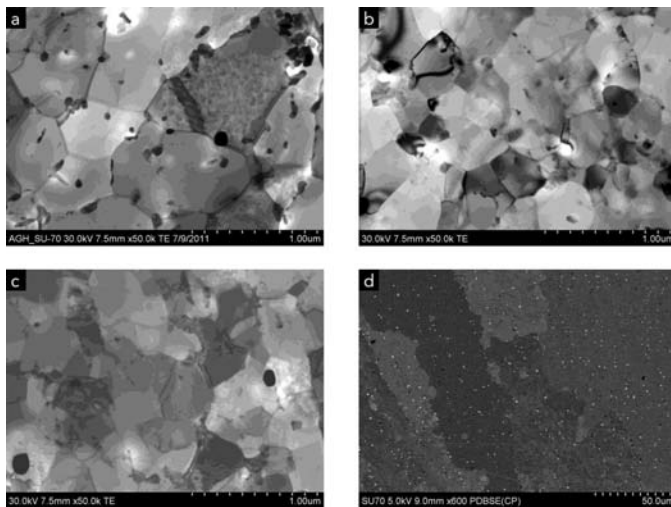


Fig. 4. Structure of 5083RS alloy subjected to different processing routes: a) after extrusion at  $400^\circ\text{C}$ , b) after extrusion and one-step procedure of thermal treatment, c) after extrusion and two-step procedure of thermal treatment, d) after extrusion and annealing at  $500^\circ\text{C}$

TABLE 2  
Mechanical properties and corresponding average grain size of the 5083RS alloy subjected to different processing routes

Preparation route	UTS [MPa]	YS [MPa]	Elongation [%]	Grain size, d
Extr. + $500^\circ\text{C}$ ann.	325	130	23	$100\ \mu\text{m}$
As-extruded	430	320	20	710 nm
1 step route	450	373	15.5	360 nm
2 step route	459	419	12	270 nm

Stress-strain characteristics for all tested materials are shown in Figure 5. Serrated flow of the material is characteristic phenomenon for Mg rich aluminium systems [10]. Calculated values of yield strength ( $\sigma_{0.2}$ ), ultimate tensile strength ( $\sigma_{UTS}$ ) and elongation to failure ( $\epsilon_f$ ) are presented in the Table 2. Material processed by one and two-step thermo-mechanical procedure exhibit much higher mechanical properties. It can be noticed that increment of mechanical parameters by 30% results in simultaneous decrease of plas-

ticity. Specimens annealed at  $500^\circ\text{C}$  show substantial loss of the mechanical properties.

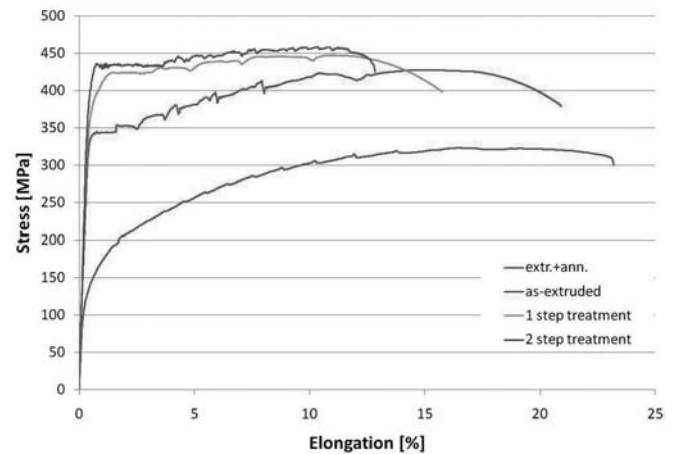


Fig. 5. Tensile stress – strain curves of as extruded and after thermo-mechanical treatment of 5083RS alloy

The 0.2% proof strength of RS 5083 alloys exhibits grain size dependence according to Hall-Petch relationship, as shown in Figure 6. In the present study, the experimental Hall-Petch relationship is expressed as  $\sigma_{0.2} = 118.7 + 4898d^{-1/2}$ , namely, the  $\sigma_0$  and  $k$  are 118.7 MPa and 4898 MPa  $\text{nm}^{1/2}$ , respectively.

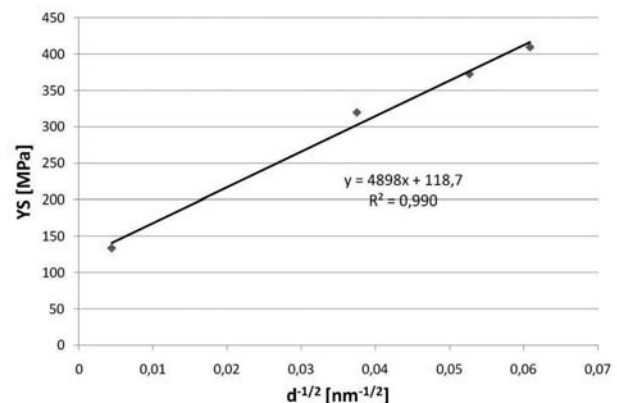


Fig. 6. Dependence of the yield stress (measured at permanent elongation of 0.2%) on the average grain size of 5083RS alloy

#### 4. Discussion

It is well known that application of rapid solidification techniques for processing of aluminium alloys gives positive effects, especially in terms of mechanical properties of material. In correspondence to the conventionally cast material, 5083 RS alloy exhibit 45% higher yield strength and 25% higher ultimate tensile strength without significant decrease of plasticity [6]. Those features are direct results of the grain size refinement from an average diameter of  $\sim 15\ \mu\text{m}$  to  $\sim 710$  nm for conventionally cast and rapidly solidified alloy, respectively.

It is known that ultra-fine grained materials are temperature sensitive and triggering off recrystallization process occurs with ease at elevated temperatures, however in the present study relatively high thermal stability of RS materials is observed. Such behaviour is ascribed to additions of

transition metals such as Fe, Mn and Cr which forms highly dispersed intermetallic phases that provide thermal stabilization by the grain boundary pinning. Previous research results focused on detailed study of thermal stability show that RS materials exhibit elevated temperature stability up to 450°C [6].

It has been already recognized that thermo-mechanical treatment of as-cast 5083 alloy leads to substantial grain refinement from initially coarse structure with a grain size of  $\sim 50\mu\text{m}$  to the level of several micrometers (e.g.  $\sim 6\mu\text{m}$  after rolling and annealing procedure [8]). Results presented in this paper emphasize that similar grain refinement can be obtained by rapid solidification combined with hot extrusion process. Moreover, application of two-step thermo-mechanical treatment allows for further reduction of grain size to the level of  $\sim 270\text{ nm}$ . Effective grain refinement of 5083 alloy to nanometres regime is reflected in the enhancement of the yield stress of tested material, however significant drop of plasticity is observed.

## 5. Conclusion

Rapid solidification process combined with plastic consolidation by hot extrusion leads to an effective grain size refinement of 5083 alloy. As results, enhancement of mechanical properties is observed without significant decrease/drop of plasticity. Further increase of mechanical properties has been achieved by application of two steps thermo-mechanical treatment. It has been shown that the yield strength increases from 320 MPa to 419 MPa, however simultaneous decrease of ductility from 20% to 12% has been observed.

Relatively high thermal stability of RS 5083 material has been noticed. This effect is attributed to the presence of very fine intermetallic, below 100 nm in size, particles which effectively suppress grain boundary mobility at elevated temperatures [11].

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