RESEARCH PAPER

The Effects of Rapid Solidification on the Microstructure and Mechanical Properties of Al5083

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Abstract: *In the present study, bulk refined-structured Al 5083 alloy with high mechanical properties was successfully fabricated by a hot consolidation process of nanostructured melt-spun flakes. The influence of the cooling rate and pressing conditions on the microstructure and mechanical properties of the alloy were investigated using X-ray diffractometer (XRD), optical microscopy (OM), field emission scanning electron microscopy (FE-SEM), microhardness, and compression tests. Rapid solidification combined with the hot consolidation at T= 753 K (480°C) and P= 800 MPa for 20 min produced a bulk sample with the desirable bonding, good microhardness (184.2±12.4 HV), and high strength (273±8 MPa) combined with 7 pct. fracture strain. These amounts are 78.6±5.1 HV, 148 ±9 MPa, and about 5 pct. for the as-cast sample. Microstructural refinement during the controlled consolidation of nanostructure rapidly- solidified flakes contributes to such high mechanical properties of the bulk sample.*

Keywords: *Rapid solidification, Aluminum alloy 5083, Mechanical properties, Microstructure, Hot consolidation.*

1. INTRODUCTION

Aluminum and its alloys as the most popular nonferrous metal are favorable choices for many fields such as packaging, aerospace, and building transportation due to its rich resource, lightweight, good mechanical properties, and suitable corrosion resistance. Although the growing use of composites is considered, aluminum is still one of the most important structural materials in the aerospace industry [1-4].

Al 5083 alloy has been widely used due to good ductility, formability, weldability, toughness, and corrosion resistance. It is an Al-Mg-based aluminum alloy with an intermediate level of Mg content (4–5 wt.%) and a relatively high content of Mn (0.4–1.0 wt%) [5-6]. Solution strengthening and work hardening for 5xxx Al alloys due to lack of precipitation strengthening mechanism are the only available options for enhancement of their mechanical properties. However, it has been found that the application of non-standard processing techniques such as rapid solidification RS followed by the plastic consolidation PC can improve the mechanical properties of the alloys by microstructural refinement [4, 7-8]. To improve the strength and plasticity of the Al alloys simultaneously, grain refinement is an important choice [1]. In recent years intensive research has been devoted to the innovative processing that successfully improves the strength of Al-Mg alloys via microstructural refinement. Rapid solidification processes are an important route to modify the microstructure and improve the mechanical properties of the alloys [9-14]. The increased tensile and shear strengths of nanocrystalline and ultrafine-grained materials in comparison to those of conventional materials of the same composition are the primary reasons for their potential usage in structural applications [15].

Melt spinning is the most usual process of rapid solidification methods that leads to significant modification of the microstructure [16]. A high cooling rate during melt spinning (105–106 Ks^{-1}) leads to the refinement of the microstructure, extending the solid solubility of the alloying elements and reducing the level of segregation, which enhances mechanical properties [16-17]. Moreover, melt spinning has the ability to produce a large quantity of rapidly solidified ribbons. Melt spinning has attracted particular attention for Al alloys due to their lightweight

[18]. However, as the melt-spun alloy is usually in the shape of flakes or ribbons, a consolidation method is required to produce a bulk material with the capability of structural application [19]. The compaction techniques need high pressure and quite high temperature for densification and workability of the material, respectively and plastic deformation leads to better bonding due to material flow. The particles slide or shear over each other, which assist in better bonding and lead to removing the oxide surface layers [20].
There are many studies on improving the Al 5083 alloy through different methods due to the demand for a high-quality alloy [4, 14, 18], but few about the simultaneous effect of rapid solidification and hot consolidation processes on the microstructure refinement of the Al 5083 alloy with the capability of industrial application. Therefore, in the current study hot press was used to consolidate nanocrystalline Al 5083 flakes to achieve dense bulk refined Al alloy with enhanced mechanical properties. For this purpose, the mechanical behavior of the bulk samples has been evaluated through microhardness and compression tests. The correlation between microstructure and properties of the resultant bulk Al 5083 alloy were also compared with the conventional as-cast and rapidly solidified microstructures.

2. EXPERIMENTAL PROCEDURES

Table 1 lists the composition of a commercial aluminum 5083 alloy supplied in the as-cast state material. Ribbons with a thickness of about 10 μm, width of about 1 mm, and length of several meters were produced using a chill-block melt-spinning device. For this purpose, the alloy inside the nozzle was melted by induction coils, pushed out of a nozzle hole under the argon gas pressure of 0.4 bar, and ejected onto the surface of a rotating copper disk (ϕ 25 cm). The ribbons were cut into flakes and cold pressed at room temperature (RT) and P= 800 MPa for 5 min as a pre-consolidation process to produce green cylinders with approximately a height of 15 mm and diameter of 10 mm. The green compacts were then hot pressed at a heating rate of 20 K min^{-1}, T= 723 K (450°C), P= 600 MPa for 20 min (Uniaxial WEBER PWW machine).
Structural evaluation of the sample has been done by Philips, PW1800, Cu-Kα (λ= 1.54 Å) X-ray device at 30 mA and 40 kV. An optical microscope (Neophot 32) was used for the microstructure characterization of the sample. Modified Keller's solution was used for about 5 s as the chemical etchant. FESEM examinations were applied by a 200 FEI ESEM QUANTA scanning electron microscope at 25 kV connected to the 2017EDAX EDS Silicon Drift. Moreover, an MKV-21H microhardness device was performed using 10 g force. An INSTRON 8562 testing facility at a strain rate of 1×10^{-4} s^{-1} and room temperature was used to study the compression behavior of the as-cast and bulk samples (with parallel surfaces at both ends).

3. RESULTS AND DISCUSSION

3.1. Effect of Rapid Solidification on the Microstructure

Fig. 1 shows the OM microstructures of the Al 5083 at as-cast, as-spun, and hot consolidated conditions. The microstructure of the conventional as-cast sample (Fig. 1a) consists of coarse grains with an average size of 150 μm. A very small amount of intermetallics is scattered within the α-Al matrix. The location of these particles is the grain boundaries or triple junctions. The presence of $(Fe, Mn)_3SiAl_{12}$ and small Mg_2Si particles as a second phase has been reported for the alloy [21].
It is found that the cooling rate and solidification process have an important effect on the microstructure of the alloys. The structure of the as-spun ribbons is quite different from those of the conventional ones. Cross-sectional optical microscopy image of the as-melt spun ribbons (Figs. 1b) reveals that rapid solidification during melt spinning, which induces the formation of a high density of nuclei leads to the presence of a fine-grained structure. Comparing the solidification microstructure of as-spun ribbons with as-cast alloy solidified under conventional casting (Fig. 1a), shows that the coarse grains and intermetallic particles are refined significantly. As the alloying elements due to the high cooling rate have no sufficient time to precipitate from the Al matrix, they remain as solutes in the matrix leading to lower segregation. Therefore, rapid solidification of main alloy melts can result in increased refinement and chemical homogeneity of the final alloy. . From the right side of Fig. 1b, three zones are distinguished: the featureless zone

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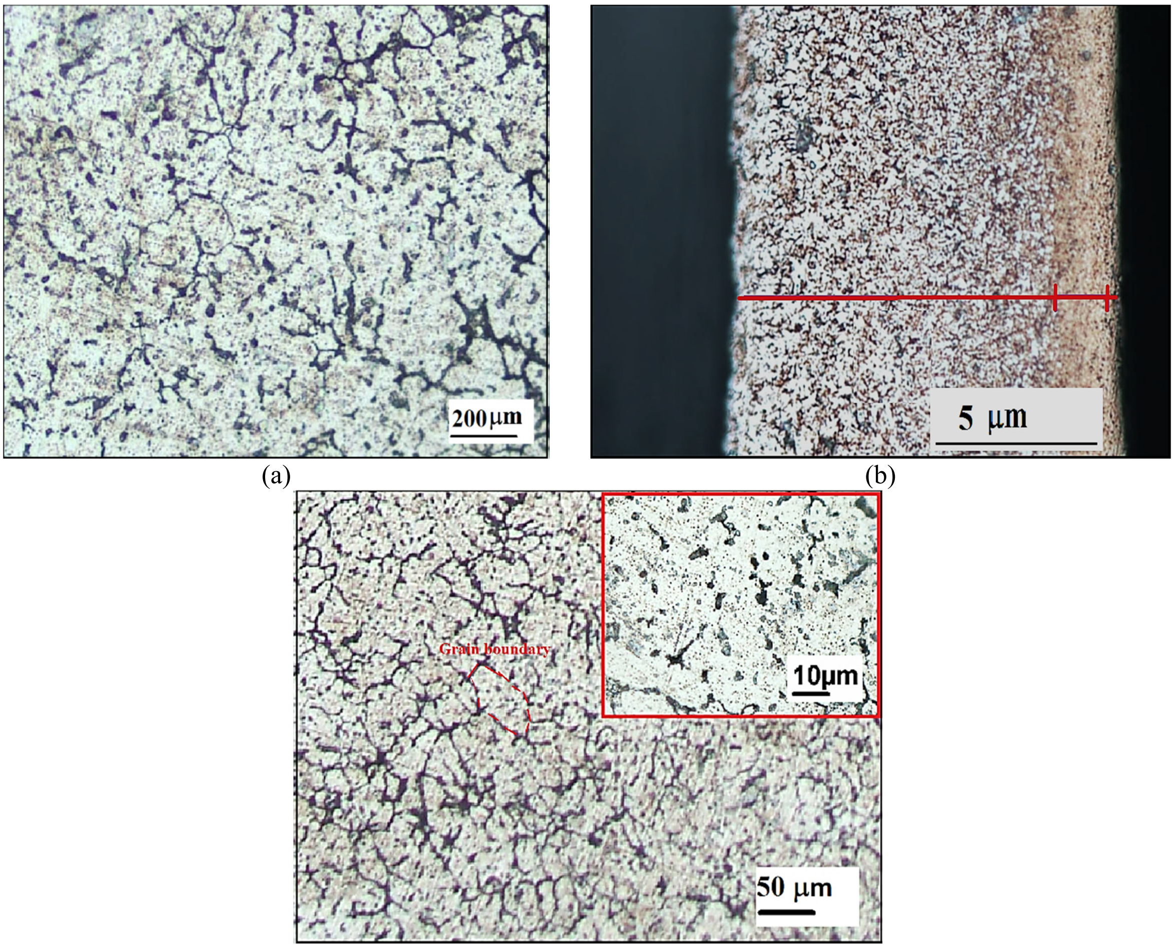
on the wheel side as a chiller, columnar grains that are perpendicularly oriented to the chill surface, and the dendritic zone. Consequently, different microstructures appear within the thickness of the ribbons due to different cooling rates. Moreover, the grain size of the hot-consolidated sample is in the range of 10 µm. It is important to notice that characteristic features of the microstructure such as grains and particle size were homogenous over the entire cross-section of the investigated profile. Very fine intermetallic phases are distributed evenly along grain boundaries. There was no indication of internal porosity, thus full plastic consolidation of flakes can be assumed.

The samples were also studied microstructurally by FESEM observation. Figs. 2a-b show the cross-sectional FESEM images of Al 5083 ribbons at different magnifications. Bright and dark precipices analyzed by FESEM can be observed in the microstructure. The fine bright phases (region 1), according to the literature [22], can be considered as some of these possible phases; α-Al15(FeMn)$_3$Si, β-Al$_5$FeSi, Al$_9$Mn$_3$Si and/or α-Al$_{12}$Fe$_3$Si. The microstructure consists of many of these bright-colored phases. The common MgSi phase in aluminum alloys is Mg$_2$Si which mainly appears in the black phase under SEM [23].

The dark contrast in Fig. 2 may also be related to the Mg$_2$Si phase (region 2). The phases are mostly smaller than 100 nm sizes. There are no large phases in the RS ribbons. It can be seen that fast cooling during melt spinning refines the intermetallic particles extremely.

Table 1. Chemical composition of Al 5083 alloy (wt.%).

Elements	Mg	Mn	Fe	Si	Cr	Cu	Zn	Ti	Al
%Wt.	4.36	0.52	0.33	0.16	0.08	0.03	0.01	0.04	Bal.



(a) (b) (c)

Fig. 1. Optical images of the Al 5083 alloy at a) as-cast, b) as- spun and c) hot consolidated conditions.

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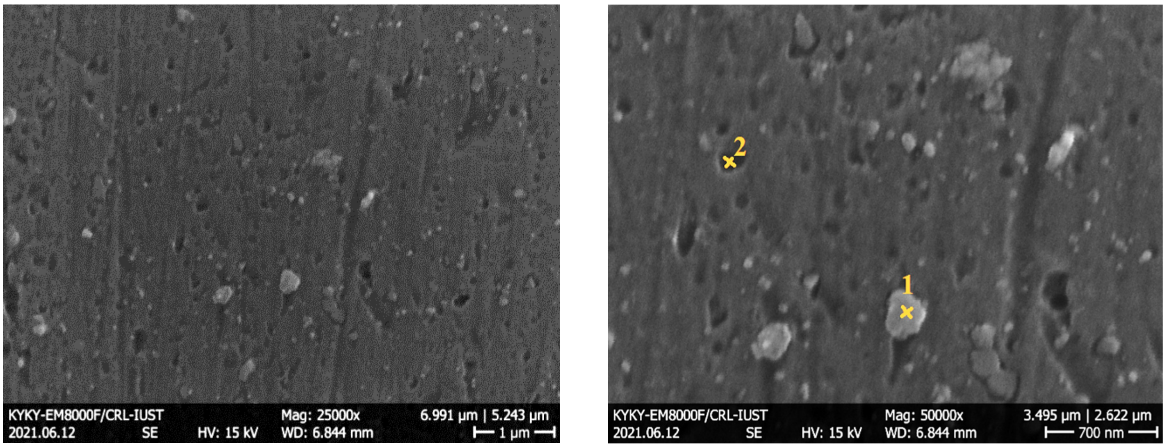


(a) (b)

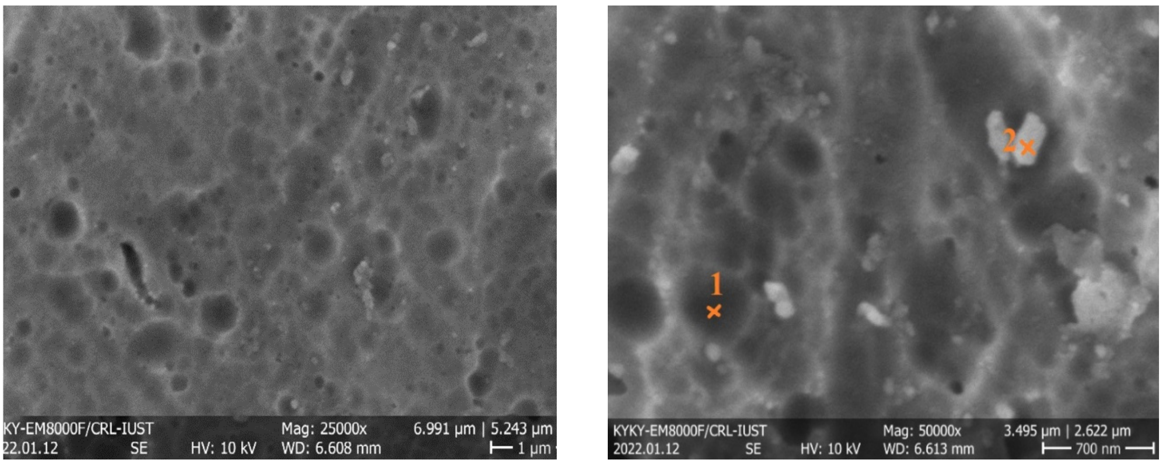
Fig. 2. a-b FESEM microstructure of Al5083 ribbons at different magnifications.

Figs. 3 a-b show FESEM images of the bulk hot-pressed sample at different magnifications. The dark (Spectra 1) and bright (Spectra 2) phases in Fig. 3b mainly contain Mg and Si and black contrast reach in Si, Mg, Fe, Mn, and Cu elements, which are likely related to the formation of Mg_2Si and other intermetallic compounds, respectively.

The growth of the intermetallic compounds, as shown in Fig. 3 takes place during the hot consolidation of melt-spun flakes. However, the microstructure is still very fine due to the effect of rapid solidification. The microstructure of conventional as-cast Al 5083 is coarse and rough and has a high degree of chemical separation. Rapid solidification leads to new microstructures, such as micro/nanocrystalline structures and semi-stable crystalline phases, which are ideal to create a homogeneous structure. Nevertheless, the dimension of the samples is always smaller than those produced by the conventional as-cast processes.

3.2. Effect of Rapid Solidification on the Mechanical Properties

Fig. 4 shows the microhardness values of the as-cast ingot, ribbons, and bulk hot-pressed Al 5083 samples at T= 723 K (450°C), P= 600 MPa for 20 min. The microhardness of the melt-spun ribbons (184.2±12.4 HV) and bulk samples (151±6 HV) are more than and about two times with respect to the conventional as-cast samples (78.6±5.1 HV), respectively. Rapid solidification during the melt spinning technique can enhance the mechanical properties through extremely low levels of segregation leading to excellent homogeneity, and structure refinement. High cooling rate results in a super-saturated solid solution of elements in the Al matrix, which increases the hardness of the nanostructured melt-spun ribbons.



(a) (b)

Fig. 3. a-b FESEM microstructure of the bulk hot- pressed Al5083 alloy at different magnifications.

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Due to the different atomic radii of elements and their interaction with dislocations a strain field will be produced which results in the solid solution strengthening. Moreover, high temperatures which are necessary for the fabrication of highly dense bulk samples during the consolidation process lead to a reduction of hardness for the consolidated bulk sample (151±6 HV) concerning the as-spun ribbons due to coarsening of the α-Al matrix and intermetallic particles. The presence of porosity in the bulk samples may also contribute to decreasing the microhardness during hot consolidation. However, the hardness of the bulk Al5083 alloy is significantly higher than that of the as-cast alloy due to the effect of rapid solidification in the final samples.

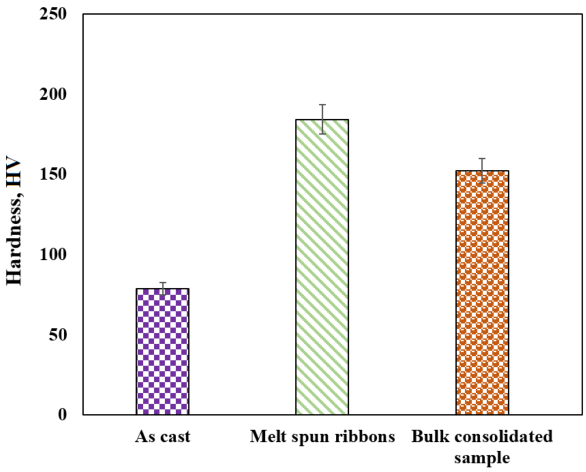

Fig. 4. Microhardness (HV) of Al 5083 alloy at condition of as-cast, melt- spun and hot pressed.

Fig. 5 shows the results of the compression test for as-cast and bulk hot-pressed samples. It can be seen that the hot-pressed bulk sample shows a yield stress of 273 ± 8 MPa and about 7 pct. plastic strain. However, the as-cast sample indicates a yield stress of 148 ±9 MPa and about 5 pct. plastic strain. The slopes of the lines in the linear-elastic portion of the curves indicating the modulus of elasticity (E) are almost close to each other. The amount, size, morphology, and distribution of the intermetallic particles in the alloys can significantly control the mechanical properties of the alloys. A combination of rapid solidification and hot pressing processes can lead to the formation of ultra-fine intermetallic phases uniformly distributed within the fine α-Al matrix that has an important role in the high mechanical properties of the bulk samples for the as-cast samples. Therefore, it can be possible to produce a high-strength Al-based bulk materials by hot consolidation of the nanostructured Al 5083 rapidly- solidified flakes.

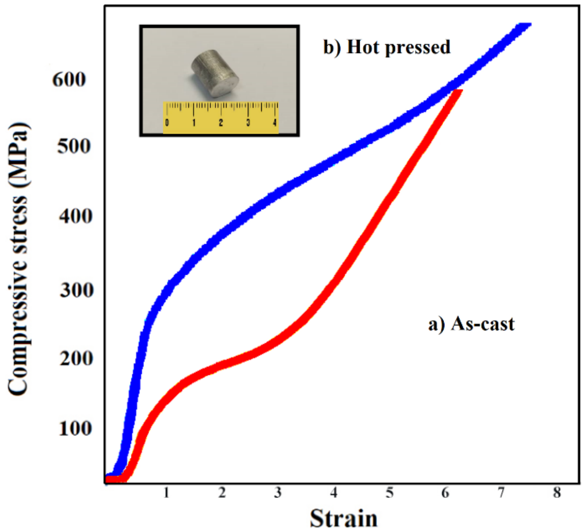

Fig. 5. Compression stress–strain curve for the as-cast and hot pressed alloys and a typical bulk sample.

4. CONCLUSIONS

1. The coarse microstructure of the conventional as-cast sample is refined significantly by increasing the cooling rate. Excellent microstructure homogeneity and ultra-fine scale and nano-sized particles uniformly distributed along the fine Al grains can be obtained in the rapid-solidified sample.
2. A rising trend of the Vickers microhardness (more than twice) in the samples during rapid solidification followed by hot consolidation (184.2 ± 12.4 HV) compared to conventional casting (78.6 ± 5.1 HV) can be obtained.
3. The homogeneous distribution of very fine intermetallic particles in the matrix enhances the mechanical properties of the alloy during rapid solidification. The mechanical properties of the bulk hot-pressed sample show enhanced yield strength (273 ± 8 MPa) without decreasing the elongation.
4. Rapid solidification combined with hot pressing processes lead to the formation of high-strength Al-based bulk materials through grain refinement strengthening, and solid solution strengthening which upscaled into an industrial manufacturing process.

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