THE INFLUENCE OF EXTRUSION RATIO ON THE STRENGTH OF HOT EXTRUDED ALUMINUM ALLOY CHIPS

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Abstract

Hot-extrusion of the chips and other highly fragmented materials is a very convenient way for aluminum alloys scarp processing. It is possible to achieve ready or semi-finished products in one step of material forming - directly from the chips to the bulk material. The mechanical properties of such processed material are affected by various extrusion conditions: temperature, extrusion speed and cross-section reduction ratio λ. The variation of cross-section reduction ratio has an effect on chips bonding quality, which in turn results in different mechanical properties. The objective of the present study is to analyze mechanical and structural features of 6060 and AlSi11 aluminum alloys after plastic consolidation by hot extrusion with different cross-section reduction ratio in the range of 7 to 45. Aluminum alloy in the form of chips, were preliminarily cold compacted to produce cylindrical billets. The as-compressed billets were then hot extruded at 450 °C. The samples cut from as extruded rods were subjected to tensile test and structural SEM observations. Based on obtained results minimum extrusion ratio required for sound bonding of chips was established.

Keywords: Aluminum chips, plastic consolidation, recycling, aluminum alloys

1. INTRODUCTION

Nowadays, market share of aluminum recycling products grows continuously. The main driving force of new recycling technologies development is highly energetic process of primary aluminum production. Majority of existing aluminum recycling technologies is based on re-melting. Due to oxidation and substantial material losses this approach is problematic in the case of highly refined wastes such as chips and foils. In order to overcome these problems solid state recycling (SSR) technique is proposed. In general, SSR rely on hot extrusion process that omits liquid state of material. Lower temperature used in this approach ensures minimization of oxidation and material losses during processing.

Plastic consolidation is well established technique for bulk material production from various dispersed forms of light alloys, i.e. powders [1], flakes [2-3]. Based on this approach materials with unique properties can be achieved [5-6]. The major goal of plastic consolidation in application to chips recycling is to obtain sound, bulk material with properties not worse than those received for conventional alloys. For this purpose, series of requirements need to be met. In particular, plastic consolidation conditions must be precisely determined.

In this work, the influence of various extrusion ratios on the profiles quality was tested. Two most common materials, i.e. as cast 413.0 and 6060 wrought aluminum alloys were used. As a result, critical conditions for plastic consolidation of chips were determined.

2. EXPERIMENTAL PROCEDURE

The AA6060 and 413.0 aluminum chips were produced during turning process with cutting tool feed rate of 0.2 mm/s and rotation speed of 315 rpm. In order to minimize influence of impurities during consolidation dry machining was performed. As machined chips (**Fig. 1a, 1b**) were preliminary compacted by cold pressing under the pressure of 240 MPa. As a result cylindrical billets of 40 mm in diameter and 10 mm in height were produced (**Fig. 1c, 1d**). Multilayer compaction process was adopted in order to obtain relatively high, approximately 80% of theoretical value of billets density.

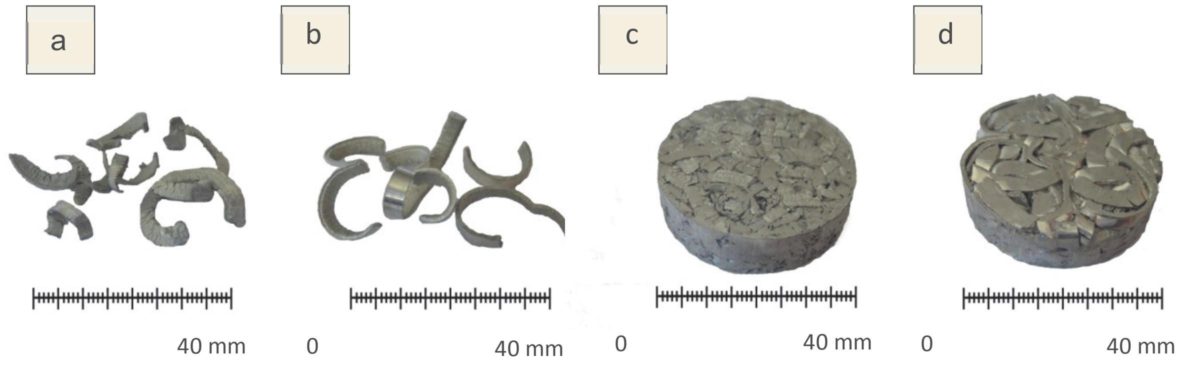

Fig. 1 Macro-view of as machined chips from a) 413.0 and b) 6060 alloy. Cylindrical billets of as compressed: (c) 413.0 and d) 6060 alloy

As compressed billets were then extruded by using following conditions: temperature of 450 °C and ram speed of 13 mm/s. As a result of extrusion, series of rods with the cross section reduction ratio of λ = 7, λ = 11, λ = 16, λ = 25 and λ = 45 were produced. Series of tensile test samples with a diameter of 5 mm and gauge length of 25 mm were machined from as-extruded rods. Uniaxial tensile tests were carried out at room temperature at a constant strain rate of $8 \cdot 10^{-3}$ s^{-1} using Zwick Z050 testing machine. Microstructure observations were performed by using Hitachi Su-70 scanning electron microscopy. Longitudinal cross-sections of samples were grinded and polished with a diamond suspension in order to obtain good surface quality for SEM studies.

3. RESULTS AND DISCUSSION

3.1. Extrusion force

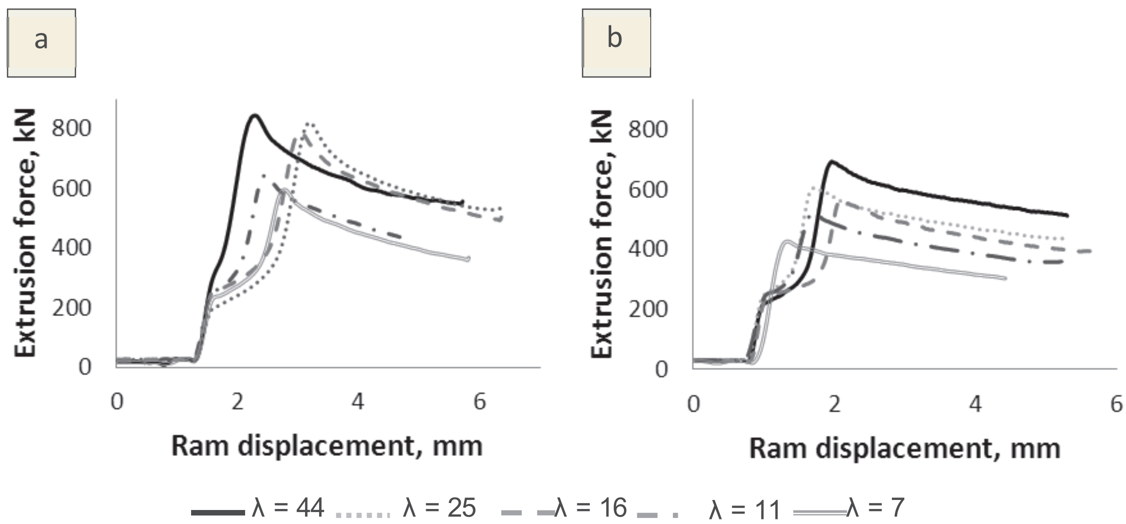

Fig. 2 Evolution of extrusion force in relation to ram displacement for a) 413.0, b) 6060 material

The relationship between extrusion forces in a relation to ram displacement for both tested materials is shown in **Fig. 2**. It can be seen that increasing of extrusion ratio leads to the enhancement of extrusion force which is typical behavior for direct extrusion process. Consequently, the higher λ is applied the higher deformation is induced, which in turn results in increasing of extrusion force. Linear relation at the beginning of a force-displacement curve is associated with a billet compaction inside of the press container. As can be seen materials extruded with λ = 44 exhibit the highest extrusion forces with a value of 853 kN for 413.0 and 694 kN for 6060. Finally, comparison of extrusion force behavior for individual alloys shows that force for every λ is always higher for 413.0 than for 6060 alloy. These differences may result from Si and Al-Fe-Si particles present inside of the 413.0 alloy. Fine, hard and brittle phases may suppress plastic flow during extrusion so that higher force needs to be used in order to allow material deformation.

3.2. Surface of as-extruded rods

Fig. 3a shows macro observations of 413.0 rods extruded with different reduction ratio λ. Profiles with higher λ (44, 25, 16) present smooth and glossy surfaces without visible cracks or discontinuities. At the same time extrudates with λ = 7 and λ = 11 exhibits characteristic serration on surface which may suggest lack of sound bonding along longitudinal cross-section across profile. The lack of good consolidation is a direct result of insufficient deformation value. Coarse, brittle particles in 413.0 alloy such as Si and Fe rich intermetallic phases also constitute barrier against proper bonding. Additionally, at the beginning of every profile lack of consolidation in a form of „transition zone" can be observed [7]. In this areas gradual chip welding is being observed which results from increasing temperature and strain magnitude at the starting stage of extrusion. Change of λ in case of 6060 (**Fig. 3b**) alloy had no effect on profiles surface quality. All rods produced from this material distinguished itself with smooth and glossy surface.

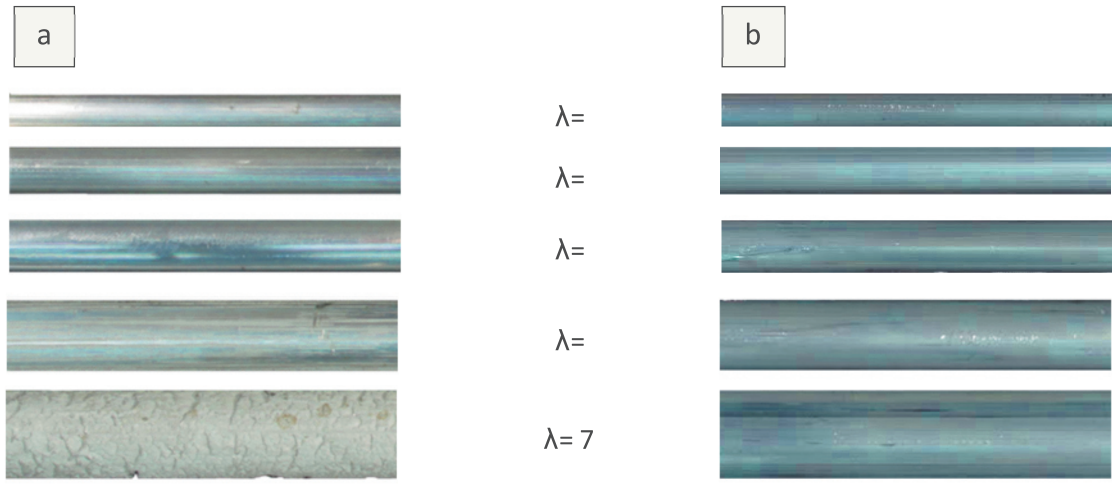

Fig. 3 Surface quality comparison of as-extruded rods from a) 413.0, b) 6060 alloy

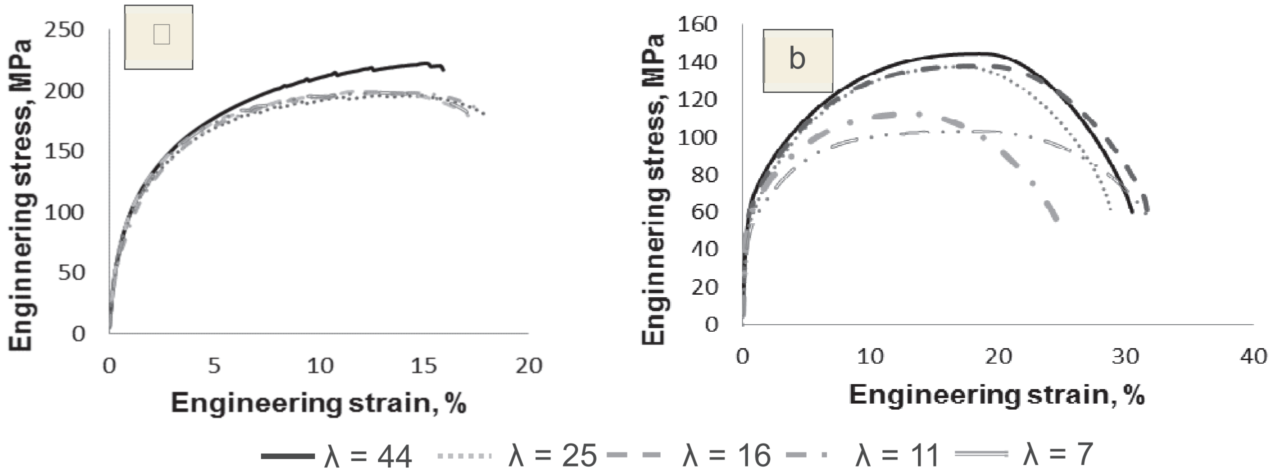

Fig. 4 Engineering stress-strain curves for a) 413.0 b) 6060 profiles

3.3. Mechanical properties

Stress-strain curves for both materials after uniaxial tensile test are shown in **Fig. 4**. The summary of the mechanical properties under tension including the yield stress (*YS*), ultimate tensile strength (*UTS*) and strain to failure (*ε*) is given in **Table 1**. The results reveal that profiles extruded from 413.0 alloy exhibit higher mechanical properties in comparison to 6060 alloy. Highly refined structural constituents influence mechanical properties as evidenced by *YS* and *UTS* (**Table 1**). Increasing of λ to 44 results in significant increase of ultimate tensile strength, which approaches ~220 MPa. Independently of cross section reduction λ, yield stress is maintained almost at the same level (**Table 1**). 6060 alloy shows qualitatively similar dependence on the *YS* and *UTS* behavior as 413.0 alloy. Continuous increase of strength parameters with increasing of λ is observed (**Table 1**). The YS increases from 55 MPa to 65 MPa and *UTS* from 103 MPa 146 MPa between λ = 7 to λ = 44.

Table 1 Mechanical properties of 6060 and 413.0 profiles after different extrusion ration

Extrusion ratio	*YS* (MPa)		*UTS* (MPa)		*ε* (%)		Maximum extrusion force (kN)	
	413.0	**6060**	**413.0**	**6060**	**413.0**	**6060**	**413.0**	**6060**
λ = 7	84.2	54.5	199	103	15.3	32.3	613	429
λ = 11	74.3	61.2	199	113	17.8	25.4	654	531
λ = 16	79.9	57.8	200	137	17	31.4	802	574
λ = 25	83	57.8	196	139	18.1	29.5	827	606
λ = 44	81	65	222	146	16	31	853	694

3.4. Microstructure observation

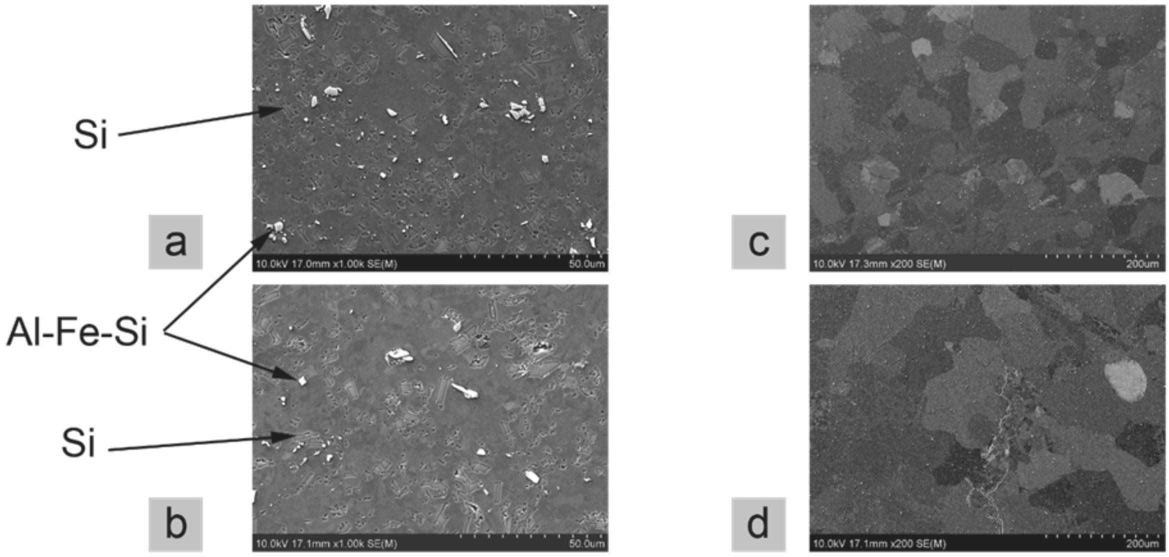

Fig. 5 Microstructure of as-extruded rods from a) 413.0, λ = 44; b) 413.0, λ = 7; c) 6060, λ = 44; d) 6060, λ = 7

Fig. 5 presents microstructure of as-extruded 413.0 and 6060 aluminum alloy. White phases visible in the microstructure of 413.0 alloy were found to be Al-Fe-Si intermetallic phases, while light grey particles are silicon crystals (**Fig. 5 a, b**). Both kinds of particles are homogeneously distributed in aluminum matrix. Size and shape of particles remains invariable regardless of different cross section reduction ratio used in the extrusion processing. Microstructural observations are in agreement with mechanical properties results, which indicate no significant difference between properties of 413.0 alloy through different λ (**Fig. 5 a, b, Table 1**). Voids, pores or cracks were not detected in the material, which suggests good overall quality of plastic consolidation (**Fig. 5 a, b**).

Comparison of the microstructure of 6060 profiles extruded with λ = 7 and λ = 44 is shown in **Fig. 5 c, 5 d** respectively. One can observe that the grain size decreases with increasing reduction ratio, which in turn provides effective strengthening of the material. In case of the lowest extrusion ratio of 6060 material numerous voids are observed (**Fig. 5 d**). Significantly lower volume fraction of particles is observed for 6060 alloy, thus the strength of the material is mainly controlled by grain boundary strengthening.

4. CONCLUSION

1) Surface quality of as-extruded rods from 413.0 strongly depends on extrusion ratio. In case 6060 alloy all profiles revealed smooth and glossy surface.
2) In case of 413.0 alloy lack of particles refinement after extrusion with different extrusion ratio does not influence mechanical properties. At the same time change of grain size for 6060 alloy results in those properties improvement.
3) Absence of visible voids in case of 413.0 extrudates suggests good overall consolidation quality. Mechanical properties of profiles extruded with cross section reduction of λ > 7 are at similar levels. However, good surface quality is obtained for λ > 16.
4) For all extrusion ratio values used in experiment good surface quality of 6060 profiles was achieved. In case of the lowest extrusion ratio numerous cracks are observed, which manifests itself in lower mechanical properties.

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