MECHANICAL PROPERTIES OF SOLID STATE RECYCLED 6060 ALUMINUM ALLOY CHIPS

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Abstract

Plastic consolidation offers good alternative for traditional scrap recycling, especially for the highly fragmented forms of materials obtained from machining process. In this method aluminum chips are being pre-compacted into a form of solid billets and then hot extruded at elevated temperature. Present work describes influence of the temperature and extrusion speed on the mechanical properties of flat 6060 aluminum alloy bars. In order to test different materials morphology, profiles were extruded from two distinctive types of scraps: large chips produced by means of turning process and fine ones produced by CNC machining. Before plastic consolidation chips were pre-compacted to the form of billets with a diameter of 40 mm. Cold compacted billets were then extruded at temperatures of 400°C and 450°C with a press ram speed of 3 mm/s. Extrusion ratio of 25 was kept constant during all experiments.

Results revealed that mechanical properties of fine chips extrudates exhibit similar properties to those obtained by casting and extrusion procedure. On the other hand, samples prepared from large chips are characterized by lower mechanical properties. Density measurements combined with microstructure observations revealed a very well consolidated material without any porosity, which suggests good quality of chips bonding.

Keywords: recycling, plastic consolidation, hot extruded, aluminum chips

1. INTRODUCTION

Although aluminum recycling history dates back to the early twentieth century, this process became more important in the years following World War II as a result of increased demand for this product. Nowadays, scrap as an aluminum supply still has a powerful interest since production of aluminum from secondary (recycled) sources requires much smaller energy than well known Bayer process [1]. Furthermore, the efficient production of aluminum recycling benefits the environment by preserving natural bauxite ores.

Actually, the recycling process of aluminum is mostly focused on commercially grade 3000, 5000 and 6000 aluminum alloys because of higher tolerance for impurities. However, in the case of special alloys, e.g. 7475, 7055 etc., where the chemical composition is strictly specified, even a small amount of impurities are unacceptable. The particular difficulty is made by iron inclusions. Many commercial alloy specifications call for low iron content, unfortunately subsequent melting operations results in continuous increasing of iron impurity because of the direct contact of scarp with the recycling separation systems [2].

The advantages of aluminum recycling make it very attractive, thus the usage of aluminum scraps constantly growing, however there are still some issues which needs to be overcome. Firstly, waste segregation. There have been a lot of work done in this area, however requirements for an easy and effective segregation process of Al wastes is still valid. The second problem is irreversible metal losses during re-melting process. Intensive oxidation, contraction cavities, risers etc., can cause even 55% losses of initial aluminum charge. Therefore, new methods of aluminum recycling are especially welcome [3]. Plastic consolidation were found to be very promising method for aluminum recycling. The idea of plastic consolidation (PC) was established by M. Stern in 1945 and is based on preliminary compaction of fine material followed by hot extrusion. The main advantage of the plastic consolidation over traditional recycling techniques is elimination of melting process, which in turn results in significant reduction of material losses during processing. Further potential advantages are: minimize energy usage, no requirement for specialize equipment and manufacturing the high quality products at the lowest possible cost [4]. PC has been already successfully deployed in a production process of rapidly solidified materials [5-7] as well as mechanically alloyed composites [8]. Application of this consolidation technique results in improved mechanical properties of materials. In this paper, two fraction of chips produced from 6060 aluminum alloy were subjected to plastic consolidation at different extrusion conditions. Effectiveness of plastic consolidation is discussed based on fracture surface observations combined with the mechanical properties results.

2. EXPERIMENT

The chemical composition of tested alloy is given in Table 1. Material in the form of ingots was processed by machining and as a result two fractions of chips were obtained, i.e.: large and fine. Large chips, characterized by slightly curved shape (Fig.1) were obtained by turning process realized with the cutting tool feed rate of 0.2 mm/s and rotation speed of 315 rev./min.. The average size of large chips was determined to be 97.4 x 3.1 x 0.72 mm. Fine, rectangular shape chips were produced by milling CNC machine operated with the cutting speed of 28 000 rev./min. The average size of fine chips determined by sieve analysis was estimated to be in the range of 0.40 - 0.315 mm. As-machined chips were preliminary compacted by cold pressing under the pressure of 240 MPa. As a result billets, 70 mm in height, 40 mm in diameter, weight of 25 g were produced. Density measurements were performed for as-compressed billets and the density of 1.81 g/cm^3 and 1.78 g/cm^3 were obtained for large and fine chips, respectively. Billets were then hot extruded at the temperature of 400 ° C and 450 ° C with the ram speed of 3 mm/s. Billets before extrusion were pre-heated for 20 minutes in the press container in order to obtain uniform temperature distribution. As a result of extrusion process rectangular shape extrudates were received. Profiles were water quenched immediately after extrusion process. In this condition series of tensile samples of gauge length 2 x 8 x 45 mm were machined. The specimens were deformed by using Zwick Z050 machine under uniaxial tension at room temperature, at a constant strain rate of 8 × 10^{-3} s^{-1}. The tensile axis was parallel to the extrusion direction. For comparison purposes, as cast material produced under the same temperature and ram speed condition was studied as well. Hitachi SU-70 SEM was used to study fracture surfaces and microstructure of tested materials. Samples for microstructural observations were prepared by grinding and polishing of longitudinal cross-sections of tested materials.

Table 1 Chemical composition of 6060 alloy

Si	Mg	Fe	Cu	Mn	Cr	Ni	Zn	Ti	Zr	Al
wt. %										
0,49	0,4	0,22	0,02	0,03	0,009	0,003	0,04	0,011	0,011	Bal.

Fig. 1 Initial morphology of as machined and as compressed billets of (a, b) large and (c, d) fine chips

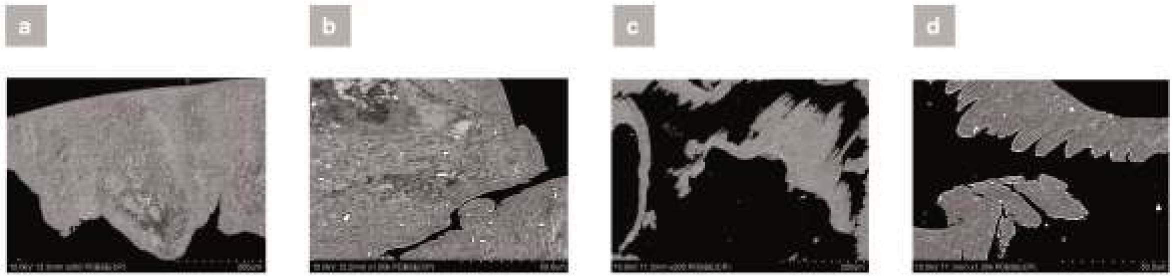

Fig. 2 SEM microstructure of as machined (a, b) large and (c, d) fine chips

3. CHIPS MORFOLOGY

Figure 1 and Figure 2 show comparison of the initial morphology of large and fine chips with it internal microstructure. One can observe that both kind of chips exhibit highly deformed microstructure as a results of high, local shear stresses generated during machining processes. It was found that the degree of deformation (γ) strongly depends on the shear angle φ and the tool back-rake angle α. High deformation introduced during machining process (γ >>1) allows for consideration of machining process as a severe plastic deformation (SPD) technique.

As machined chips differs from each other by size and outer surface (Fig. 1). Moreover, fine chips exhibit characteristics serrated segments (Fig.2 c, d) which are not observed for large chips (Fig. 2 a, b). It has been already recognized that formation of serrated chips is a result of high cutting speed typical for high-speed machining processes (HSM) [9]. The mechanism by which serrated chips are formed is explained by two different theories. One is adiabatic shear theory, which suggests that the serrated chips are caused by the periodic thermoplastic shear instability occurring within the primary shear zone [9]. The second theory is based on periodic cracks formation from the free surface of the chip and its propagation to the tool tip [9].

Cracking process is initiated for both chips, however large chips exhibit peripheral cracking character while for fine chips cracking penetrate to material (Fig. 2). White particles visible in the microstructure (Fig. 2 b, d) were found to be iron-rich phases. The size of these particles is not affected by machining process.

4. SURFACE ANALYSIS

Figure 3 shows macro observations of as extruded rods. It can be seen that independently of chips size as well as temperature and ram speed conditions, extruded profiles exhibit good surface quality. Any cracks, inclusions, pores or discontinuity are not visible on the surface. One can observe formation of “transition zone” at the beginning of extruded profile (Fig. 3 b), which is a consequence of partial chips bonding due to lower strain and temperature conditions at the beginning of the extrusion process. These defects are more pronounced for materials extruded at lower temperature, thus increasing of extrusion temperature results in improved quality of plastic consolidation. Furthermore, using die with the pre-chamber stabilizes flow of metal, which in turn results in reduction of “transition zone” in extruded profiles [10].

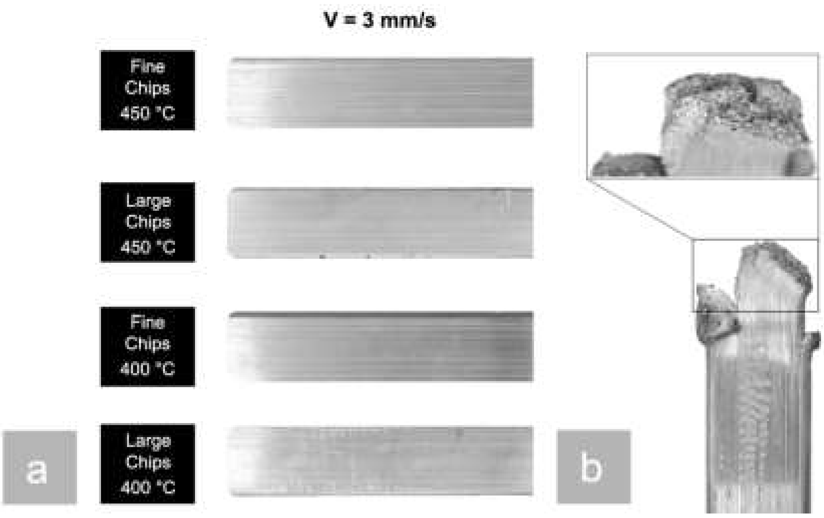

Fig. 3 a) Surfaces of as-extruded profiles b) “transition zone”

5. MECHANICAL PROPERTIES

Figure 4 shows engineering stress-strain curves recorded during tensile tests for all tested materials. The average values of Yield Stress (YS), Ultimate Tensile Strength (UTS) and Elongation (E) for all testes materials are shown in Table 2. One can observe that independently of extrusion temperature the mechanical properties of materials received from fine chips are higher than those obtained for large chips or solid materials (Fig.4, Tab. 2). Furthermore, for given chips morphology the effect of extrusion temperature on mechanical properties is negligible (Fig. 4 Tab. 2). However, there is a difference between properties of cast material extruded at 400 °C and 450 °C (Fig. 4, Tab. 2). Higher properties of extrudates at 450°C can be attributed to solid solution strengthening effect. It is assumed that higher temperature increases solubility of Mg in the aluminum matrix, thus enhancement of properties can be expected. This effect can be difficult to observe in the case of chips, because mechanical properties are results of superposition of different phenomenon’s such as: solution strengthening, work hardening prior extrusion and chips bonding quality.

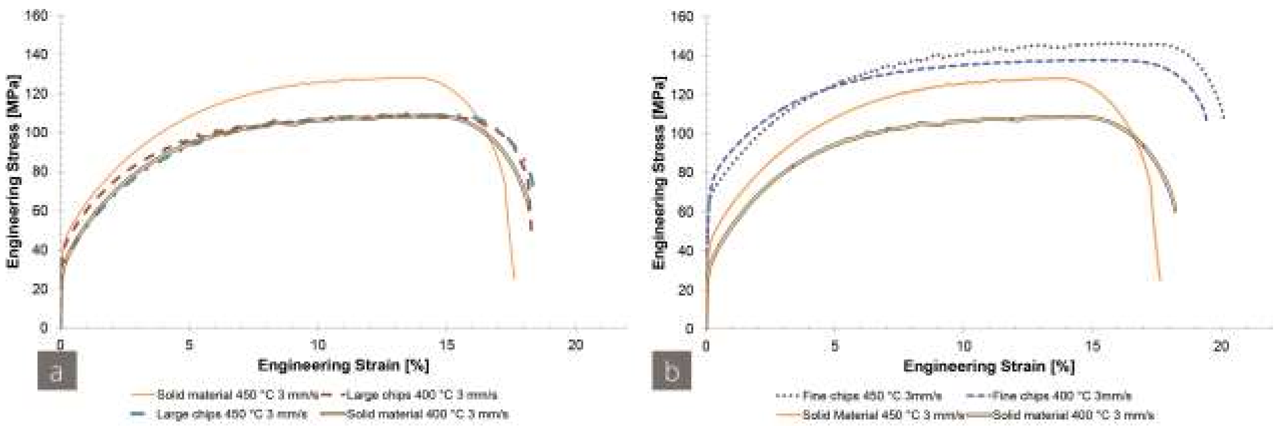

Fig. 4 Engineering stress-strain curves for exemplary samples extruded from
a) Large chips and b) Fine chips

Table 2 Mechanical properties of as extruded 6060 profiles

Material	Temperature [°C]	YS [MPa]	UTS [MPa]	E [%]
Fine chips	400 °C	77	138	19
Large chips		45	109	18
Solid material		36	109	18
Fine chips	450 °C	71	146	20
Large chips		35	110	18.5
Solid material		47	128	17

6. FRACTURE SURFACE OBSERVATIONS

Figure 5 shows SEM observations of the fracture surfaces of tested alloys deformed in tension. It is seen that the fracture surfaces of all samples exhibits predominantly ductile character with high density of micro-voids visible on the surface. Samples extruded from large chips show characteristic delaminations (Fig. 5 c), which occurs along the boundary of single chips. This suggests weaker cohesion and poor bonding between chips. Profiles extruded from fine chips show well compacted fracture surface (Fig. 5 a, b) with high density of dimple-like features. Occasionally, fine micro-cracks are detected for samples extruded at 400°C (Fig. 5 c), however increasing of extrusion temperature results in micro-cracks elimination, which indicates on the sound bonding between chips.

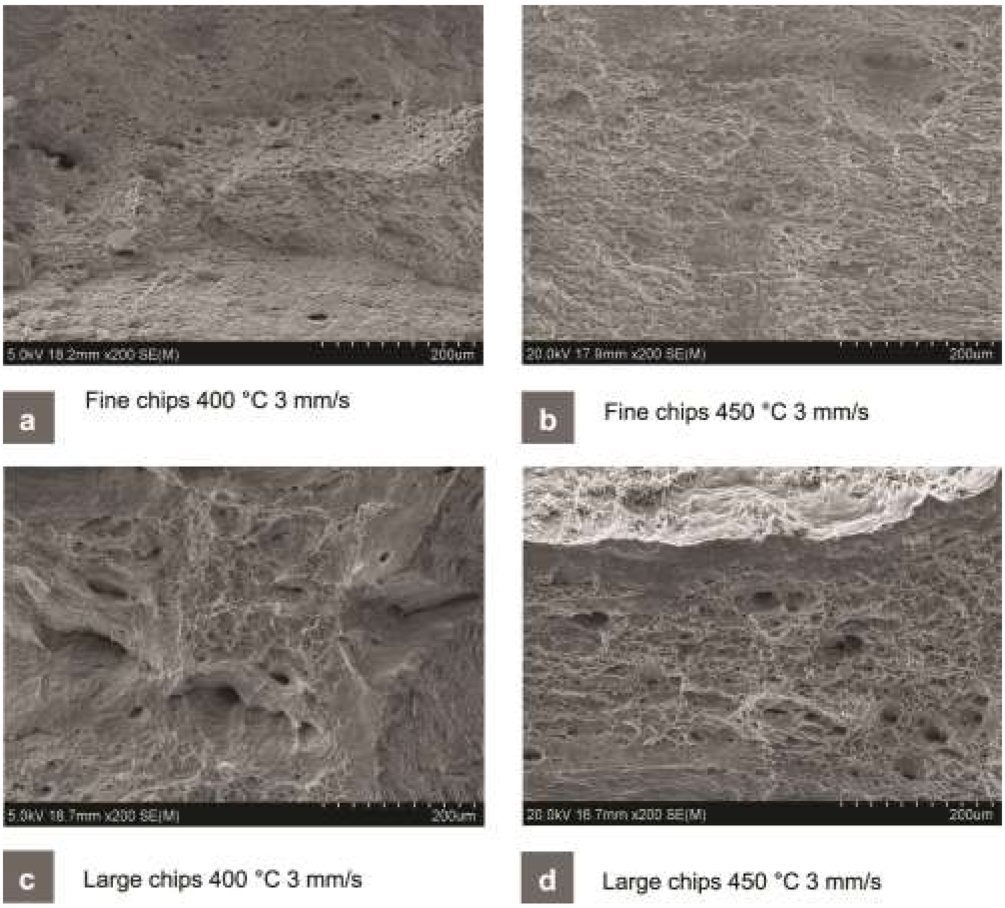

Fig. 5 SEM observations of the fracture surface of tested materials deformed under tension

CONCLUSION

1. Parameters of machining process strongly affect the morphology of chip free surface, size and its internal structure.
2. Macro observations of as extruded profiles reveal good surface quality without any visible defects.
3. Tensile test results reveal that material extruded from fine chips exhibit higher mechanical properties with comparison to large chips and solid material.
4. Fracture surface observations show effective process of plastic consolidation, particularly for materials extruded from fine chips. Large chips based profiles exhibit micro-cracks and delaminations.

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