Fabrication and mechanical testing of compacted and extruded specimens made of aluminium alloys chips

Angel Velikov[1*], Tatiana Simeonova[1, 2], Rumen Krastev[2], Tsvetan Tochev[1], Veselin Petkov[1]
[1]Institute of Metal Science, Equipment and Technologies with Hydro- and aerodynamics Centre "Acad. A. Balevski"– Bulgarian Academy of Sciences
[2]Institute of Mechanics – Bulgarian Academy of Sciences, Sofia, Bulgaria

*E-mail: anmabg@abv.bg

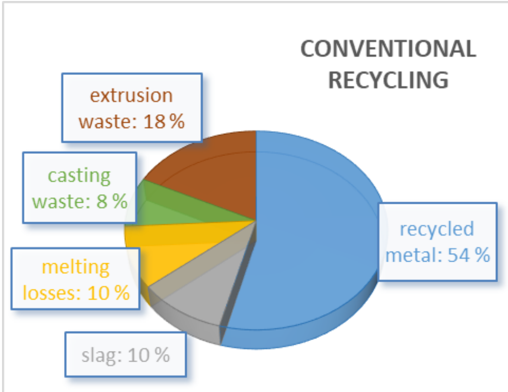
Abstract: Four types of aluminium alloys (two casting and two plastically deformable) were used in the present study. A special press mould for compacting the aluminium alloy chips and subsequent extrusion of the resulting compacts was designed and manufactured. The compressive strength of the obtained samples was investigated, in relation to their chemical composition and technological parameters during their fabrication. The results of the research are presented in tabular and graphic form. It was established that compacted samples from AW-6082, AC-48000 and AW-2024 alloy possess high compression strength (in the range of 766 - 866 MPa) under compression loading at 60% deformation. It seems that the extrusion process improves compression properties of AW-2024 and AC-48000 alloy but has negative effect on AW-6082 and AC-42000.

KEYWORDS: *ALUMINIUM ALLOYS CHIPS, COMPACTION, EXTRUSION, MECHANICAL TESTING*

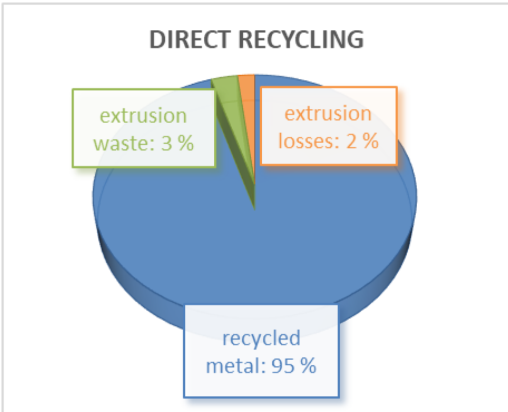
1. Introduction

The main method of recycling aluminium is through re-melting. For many years, this method has been used to recycle metal waste from the automotive industry, construction, aircraft manufacturing, metal casting and other industries, which are the main suppliers of aluminium scrap. However, there is also a significant amount of scrap (15-30 %) in the form of chips (shavings) generated by metalworking enterprises, the processing of which requires special measures. The low density of chips and their large relative surface area covered with oxides and contaminated by mechanical processing make them inconvenient to handle and transport. Their re-melting leads to additional oxidation and burning, and ultimately to metal losses reaching 50 % and more. Therefore, for more than 50 years, an increase in the chips volume density has been applied by the so-called "briquetting". Nevertheless, the loss of metal, already during re-melting is about 20 %. If losses during casting, cutting and plastic deformation (pressing and rolling) are added to this, the yield of the conventional recycling process barely exceeds 50 % (Fig. 1a) [1]. Besides, conventional recycling poses potential explosion hazards as a result of the moisture and impurities contained in the compacted chips, as well as environmental pollution from fumes and waste during the melting process. That is why, in recent years, more and more interest has been drawn by the process of so-called direct (solid phase) chips recycling. The direct recycling method avoids the energy- and labour-intensive melting process and enables the recycling of nearly 95 % of the chip scrap (Fig. 1b) [1]. It also provides for significant energy savings (26 % to 31 %) and labour costs (16 % to 60 %) compared to the process of conventional recycling [2].

The direct recycling process is relatively simple, with low energy consumption and harmless to the environment. It consists of several basic steps: cleaning and comminution of chips, cold or hot compaction followed by hot extrusion or rolling to obtain a final semi-finished product. Depending on the state of the raw materials and the selected scheme, some of the process steps may be omitted. Direct recycling of aluminium chips is still at the stage of experimental research and proving its potential for obtaining quality products. Despite the obvious economic and "green" effects, the adoption of the process by industry is slow and hesitant, mainly due to the perception that the improvement of the properties of the resulting semi-finished products has not yet been unconditionally proven.



(a)



(b)

Figure 1. *Comparison between conventional (a) and direct (b) recycling of aluminium alloy chips [1].*

The current study has two goals: (1) fabrication and (2) mechanical testing of compacted and extruded specimens made of aluminium alloys chips. Fabrication is done through cold and hot compaction, which yields two types of so-called "compacts". After that the compacts are subjected to hot extrusion to obtain the final semi-finished products.

2. Materials and methods

The compaction of aluminium chips is a process in which, by applying pressure on a mould, a workpiece with a certain shape, density and porosity is obtained. To accomplish the chips compaction, a special press mould, shown in Fig. 2, was constructed [3].

Figure 2. *Special press mould for chips compaction [3].*

Four types of aluminium alloys were used in the experiments:
- two casting types: EN AC-48000 (AlSi12CuNiMg) and EN AC-42000 (AlSi7Mg). The first one is eutectic while the second one is sub-eutectic.
- two plastically deformable types: EN AW-2024 (AlCu4Mg1) and EN AW-6082 (AlSi1MgMn).

The alloys are widely used for the production of various details in a number of industries, which implies the generation of large amount of chips during mechanical processing [4]. Fig. 3 shows the specimens obtained after compaction – one specimen from each alloy type.

Figure 3. *Specimens obtained after chips compaction.*

The compacted specimens were subjected to hot extrusion at 450°C using the same press mould, on which an extrusion nozzle was installed. The obtained specimens are shown in Fig. 4.

Figure 4. *Specimens obtained after extrusion.*

Samples with cylindrical (Ø 10 x 15 mm) and prismatic (10 x 10 x 15 mm) shape were prepared from all specimens for mechanical testing (Table 1).

Compression tests were performed on a Zwick-Roell HA-250 servo-hydraulic testing machine at room temperature. Software for compression tests according to ASTM E9 and fixed plates for compression tests up to 100 kN were used. Test speed was set at 0.01 s^{-1} for all tests and testing stages, and deformation was measured using piston displacement. Experiments were carried out up to 60% compressive deformation. Elastic modulus was determined with linear regression in the interval 30 MPa – 70 MPa.

Table 1: *Materials and samples*

Designation	Material description	Sample shape
G-AlSi7Mg	EN AC-42000 (EN AC-AlSi7Mg)	Cylindrical
G-AW6082	EN AW-6082 (EN AW-AlSi1MgMn)	Prismatic
G-2024	EN AW-2024 (EN AW-AlCu4Mg1)	Prismatic
G-AlSi12	EN AC-48000 (EN AC-AlSi12CuNiMg)	Prismatic
E-AlSi7Mg	EN AC-42000 (EN AC-AlSi7Mg)	Cylindrical
E-AW6082	EN AW-6082 (EN AW-AlSi1MgMn)	Cylindrical
E-2024	EN AW-2024 (EN AW-AlCu4Mg1)	Cylindrical
E-AlSi12Cu	EN AC-48000 (EN AC-AlSi12CuNiMg)	Cylindrical

3. Results and discussion

The average values obtained for mechanical properties of tested materials under compression loadings are presented in Table 2.

Table 2: *Mechanical properties*

Designation	Elastic modulus, GPa	Yield strength (0.2%), MPa	Compression strength, MPa
G-AlSi7Mg	6.4 ± 0.2	93± 2	555 ± 31
G-AW6082	9.3 ± 2.3	142 ± 10	829 ± 55
G-2024	6.6 ± 2.0	155 ± 20	800 ± 21
G-AlSi12	12.5 ± 0.7	130 ± 5	804 ± 4
E-AlSi7Mg	14.8 ± 1.1	93 ± 1	461 ± 43
E-AW6082	16.6 ± 1.5	96 ± 2	366 ± 90
E-2024	18.5 ± 0.5	221 ± 2	1072 ± 53
E-AlSi12Cu	18.0± 1.5	134 ± 6	945 ± 29

The strain-stress curves of compacts and tested (G) samples are presented in Fig. 5 and Fig. 6, respectively.

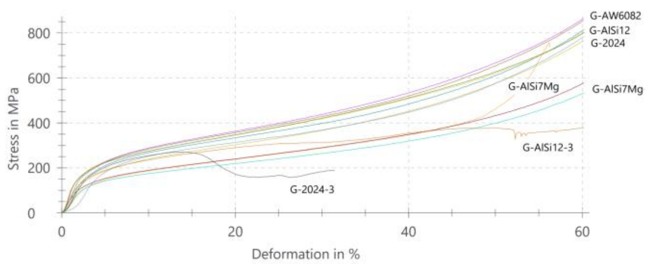


Figure 5. *Stress-strain diagrams of compacted samples (G)*

As it can be seen the best results in compression strength for compacted samples are obtained for compacted AW-6082 (samples G-AW6082), followed by AC-48000 (G-AlSi12Cu) and AW-2024 (G-2024). As a matter of fact, these three types of materials have shown very close results, in the range of 766 - 866 MPa. These results were anticipated, because two of the materials are plastically deformable wrought alloys (AW-6082 and AW-2024) and thus the process of compacting leads to production of denser semi-finished products with homogenous distribution of chips. The other two materials are casting alloys and that is why it isn’t surprise that AC-42000 show poor strength result (533 - 577 MPa), compared to the other materials. In fact, according to the EN 1706 standard “Aluminium and aluminium alloys. Castings” AC-42000 alloy possess lower mechanical properties than AC-48000 [5] alloy and thus obtained results from compression testing are in good compliance with it. The behaviour of other casting alloy, AC-48000, is quite interesting for revealing strength characteristics, comparable with plastically deformable alloys (801 - 807 MPa). This effect is probably due to the solid-solution hardening of AC-48000 alloy caused by the presence of both alloying elements cooper (precipitation-hardening by $AlCu_2$ phase) and magnesium (precipitation strengthening of matrix by Mg_2Si) in addition to the silicon that leads to the increase in hardness and strength, even at elevated temperatures [6]. The small amounts of Ni in the alloy also lead to increase in strength [6].

There are three samples that showed quite different results from the others of the same series – one of the samples from the series G-2024, G-AlSi7Mg and G-AlSi12. Those samples demonstrate behaviour, close to the non-porous materials, by reaching maximum stress after pore closing under compression and then drop in the stress, followed by fracture. The fracture occurs by forming shear faces, type of fracture that is usually observed in ductile materials [7]. This is the reason why these three samples are to be excluded from further analysis.

a) AW-2024

b) AW-6082

c) AC-48000

d) AC-42000

Figure 6. *Compacted samples (G) tested under compression load*

In order to obtain higher mechanical characteristics, compacts are additionally extruded at 450°C and tested under compression load (fig. 7). In fig. 8 it can be seen that best results in compression strength (over 1000 MPa) are observed for extruded AW-2024 (samples E-2024), followed by extruded AC-48000 (samples E-AlSi12Cu).

a) AW-2024

b) AW-6082

c) AC-48000

d) AC-42000

Figure 7. *Extruded samples (E) tested under compression load*

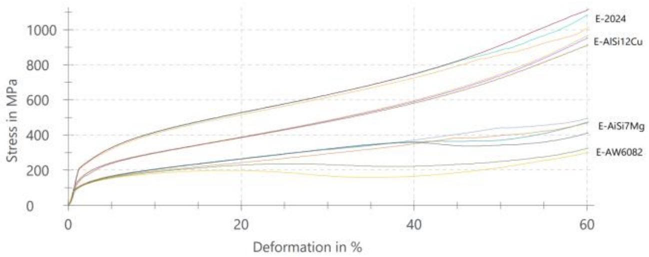


Figure 8. *Stress-strain diagrams of extruded samples (E)*

Worst compression properties, not only among extruded samples, but of all tested ones are observed for extruded AW-6082 (samples E-AW6082) and AC-42000 (samples E-AlSi7Mg). Fracture that is observed (fig. 7) for these materials reveals the presence of chips without good bonding in the volume of the samples, which are orientated along the loading axis. As can be seen in fig. 9a the fracture in samples E-AW6082 started from a crack in the centre of the samples. Microstructural study using Computer Tomography (CT) revealed a crack in the centre of the observed sample of extruded AW6082 material, spreading through the whole length of the sample. CT analysis also proved the presence of concentric cracking close to the periphery in extruded AC-42000 alloy, which explains the fracture that occurred in these samples (fig. 9b). These observations suggest that the extrusion process parameters need to be further adjusted in order to obtain better results for these alloys. The results of the microstructural study of compacted and extruded samples using micro-CT and scanning electron microscopy (SEM) will be published in a separate paper.

Figure 9a. *Sample AW-6082 before and after testing*

Figure 9b. *Fracture in extruded AC-42000 sample after testing*

It is proven, that extrusion process leads to the improvement in compression properties of AW-2024 (fig. 10) and AC-48000 (fig.11) alloys, but it has negative effect on AW6082 (fig. 12) and AC-42000 (fig. 13). When a close look on fig.11 and 13 is taken, it may be concluded that the additional extrusion process has little effect (positive in fig. 11 and negative in fig. 13) on both AC-48000 and AC-42000, which is probably connected with their characteristics as casting alloys.

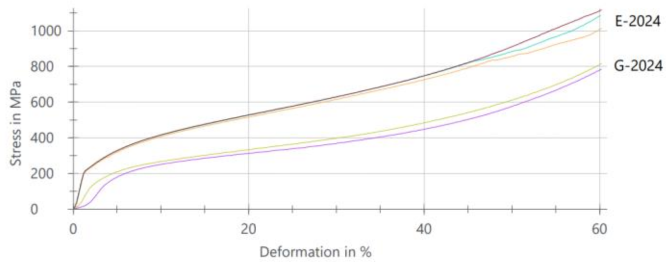


Figure 10. *Comparison of compacted and extruded AW-2024 alloy properties*

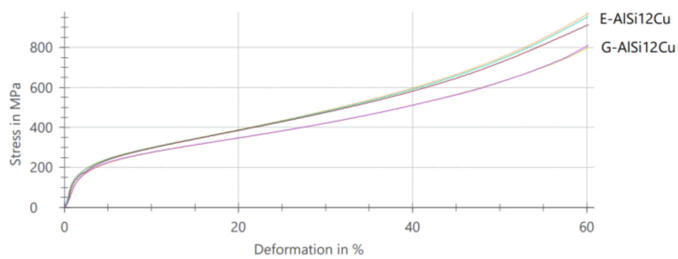


Figure 11. *Comparison of compacted and extruded AC-48000 alloy properties*

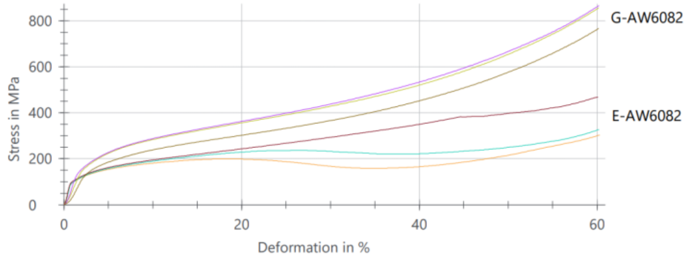


Figure 12. *Comparison of compacted and extruded AW6082 alloy properties*

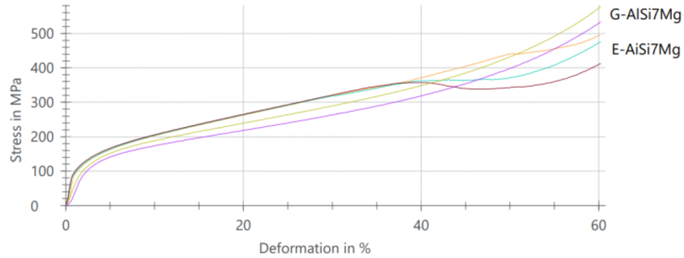


Figure 13. *Comparison of compacted and extruded AC-42000 alloy properties*

It should be noted, that both type of samples – compacted and extruded show sufficient density of the produced semi-finished products, which is concluded from missing drop in strength curves after reaching the yield point. Even though, upon deformation of 60% all tested materials show typical behaviour of porous materials with continuously rising of withstood stresses.

4. Conclusions

1. Compacted materials from AW-6082, AC-48000 and AW-2024 alloys possess high compression strength (in the range of 766 - 866 MPa) under compression loading at 60% deformation.

2. Extrusion process improves compression properties of AW-2024 and AC-48000 alloys,) but has negative effect on AW6082 and AC-42000.

3. Extrusion process does not show noticeable effect on the casting alloys (AC-48000 and AC-42000).

4. Both types of samples, compacted and extruded, show sufficient density of the produced semi-finished products, which is concluded from missing drop in strength curves after reaching the yield point.

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6. Acknowledgements

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