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# SOLID STATE RECYCLING BY COLD COMPRESSION OF AL-ALLOY CHIPS

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## ABSTRACT

*In solid state recycling material scrap from industry is recycled into new usable material without remelting. Conventional recycling, although very energy-saving compared to production from raw ore, has relatively large material waste and energy costs due to remelting process. This paper presents a short overview of main issues in solid state recycling as well as experimental research in cold compression of Al-alloy chips into solid billets. In order to examine the influence of chips' size and shape on final material properties, several different types of chips were cut. Furthermore, the influence of pressure loads on billets density was examined. Backward extrusion and free upsetting of compressed billets was additionally conducted to verify their integrity. It was concluded that in order to obtain new material usable in industry, further enhancement of materials properties is essential. Therefore, several solutions for further material processing by severe plastic deformation were proposed.*
***Key words: s****olid state recycling, chips compression, cold compression, Al-alloy chips, severe plastic deformation*

## 1. INTRODUCTION

Aluminium is the second most used metal in the world after steel. Although pure aluminium has limited usage due to its poor strength, modern industry cannot be imagined without aluminium alloys. Main advantage of Al-alloys is low density in combination with good mechanical properties and excellent corrosion resistance. Another great asset of Al-alloys is easy and cheap recyclability. All Al-alloys can be divided into two large groups: wrought alloys and casting alloys. Casting alloys contain more alloying elements than wrought. They are mostly used in transportation especially in automotive industry. Engine blocks, gear boxes, pistons and valves are often produced from these alloys. On the other hand, wrought Al-alloys require more precise alloy compiling. These alloys are widely used in building (civil construction) industry, packaging, transport and general engineering.

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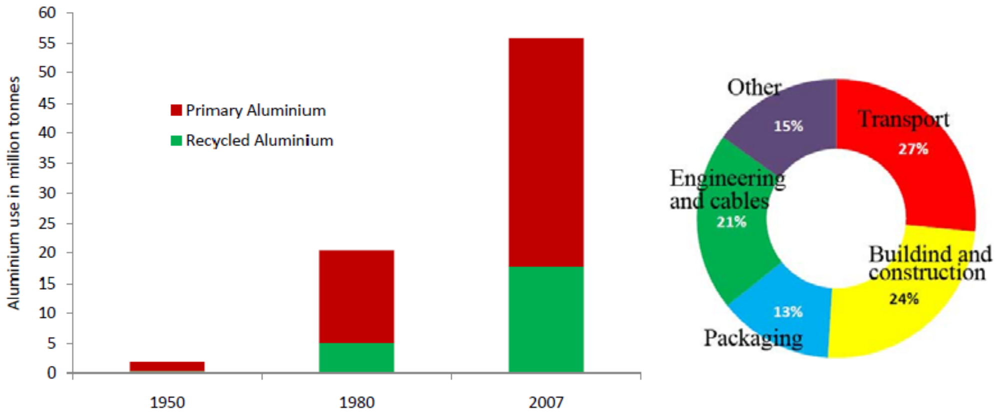



a) b)

***Fig. 1 - Field of application of aluminium alloys[1]***

Although aluminium is one of the most common elements in earth's crust, production of primary aluminium is very expensive due to large electricity consumption. In 1950s it took an amount of 21 kWh of electricity to produce 1 kg of aluminium from alumina and today that number is reduced to 13 kWh [2]. Fig. 1a shows total amount of aluminium produced (recycled and primary) in years 1950, 1980 and 2007. It can be observed that in only 27 years between 1980 and 2007, the total amount of produced aluminium was almost tripled. In Fig. 1b main application fields for all aluminium alloys are given.

Conventional recycling process uses only 5% of energy needed for primary production and emits only 5% of green-house gas [1]. This process does not deteriorate material properties and can be performed unlimited times. Beside energy savings, recycling also decreases the landfill levels.

## 2. SOLID STATE RECYCLING

In conventional recycling process about 10% of material is lost due to burning and another 10% is lost due to mixing of the material with slag. This waste is irreversible and can reach up to 35% ifmelting is performed in gas furnaces, instead of induction[3],[4]. Solid state recycling is direct recycling of the material from scrap into solid billet without remelting. In this process high pressures (and material preheating in some cases) induce chemical bonding of the material. In solid state recycling about 2-5% of the material is lost due to cleaning process and additional 3-5% is lost during forming process. Therefore, about 90% of material can be recycled, which is significantly higher compared to conventional recycling. Another advantage of solid state recycling is energy savings and therefore less environmental pollution.

The aim of this work is impose large pressures and deformation to Al-alloy AlMgSi1chips to achieve material bonding by cold upsetting. Table 1 presents chemical composition of material AlMgSi1.Alloy AlMgSi1 belongs to wrought aluminium alloys series 6xxx, which is widely used in mechanical and electrical engineering in large branch of products.

*Table 1 - Chemical composition of AlMgSi1 alloy [5]:*

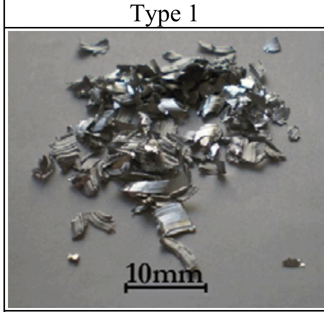
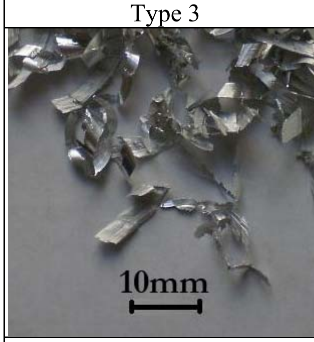
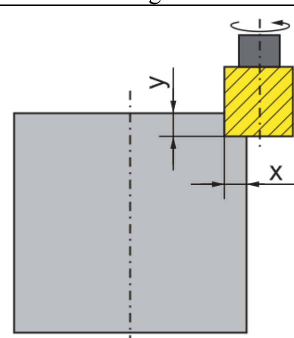
| **Element** | **Si** | **Fe** | **Cu** | **Mn** | **Mg** | **Cr** | **Ni** | **Al** |
|---|---|---|---|---|---|---|---|---|
| **%** | 0,7-1,3 % | 0,5 % | 0,1 % | 0,4-1,0 % | 0,6-1,2 % | 0,25 % | - | The rest |

In order to obtain a proper bonding, oxide layer ($Al_2O_3$) has to be broken. This thin layer is approximately 4nm thick and forms almost instantly (after 100 picoseconds) after aluminium exposure to oxygen. Aluminium oxide ($Al_2O_3$), also known as alumina, protects aluminium from further oxidation and because of it aluminium is corrosion resistant. For proper oxide braking, large deformation strains and hydrostatic pressures are essential.

## 3. EXPERIMENTAL INVESTIGATION

### 3.1 Chips formation

*Table 2–Chips and cutting parameters*

| Type 1 | Type 2 | Al-ingot |
|---|---|---|
|   |   |  |
| (y:x) -5:5mm | (y:x) - 8x7mm | |
| | | |
| Type 3 | Type 4 | Cutting scheme |
|   |   |   |
| (y:x) - 10x5mm | (y:x) - 15x5mm | |

Material was cut from ingot Ø110mm on a milling machine in laboratory for Cutting at Mechanical Faculty in Ljubljana, Slovenia. In order to obtain different types of chips, cutting parameters were varied. The turning speed of tool was set at 160 revolutions per second and feed rate at35mm/min. These two parameters were kept constant. The depth (y) and width (x) of cutting was varied (Table 2). Total of 4 different types of chips presented in table 2 were obtained. Types 1 and 2 are square shape, with type being smaller (cca. 5mm in length). Types 3 and 4 are longer and curlier.

## 3.2 Cold upsetting of chips

Compacting of chips was performed on 2,5 MN hydraulic press. Compacting was done in closed die in order to prevent deterioration of the billet. For this purpose die for backward and punch for forward extrusion were used. The tool and die diameter was □32mm.

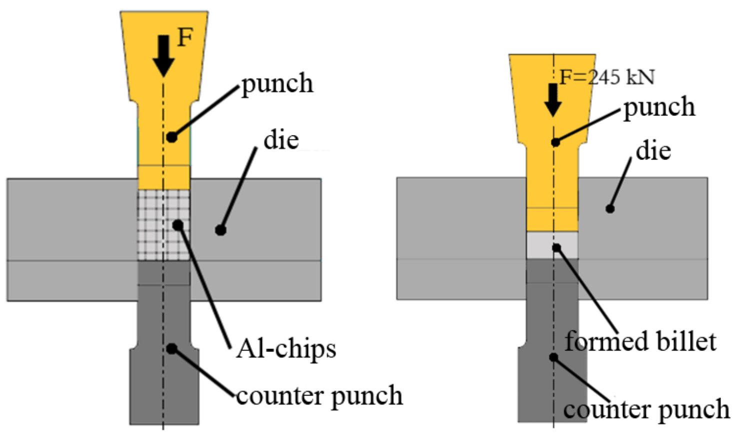
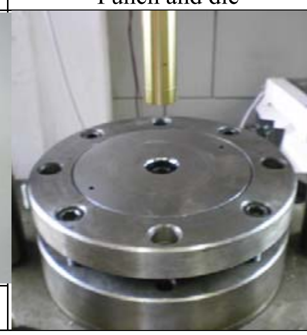



*Fig. 2 - Schematics of cold compression process*

### 3.2.1 Cold compression with 245 kN force

The aim of this experiment was to obtain solid billets with dimensions of approximately ϕ32x16mm. Based upon ending workpiece dimensions and aluminium theoretical density (2,7 g/cm3), it was calculated that required chips mass of 32 grams is needed.
Due to its low density, total amount of 32 grams of chips could not fit into the die at once. Therefore several precompacting operations were performed with lower compression loads.The final compression was performed with 245 kN load, which corresponds to 310 MPa pressure at surface area (ϕ32mm diameter). Die and punch were lubricated with Zinc stearite.
Billets' densities rose from initial pouring density of 0,4-0,6g/cm3 to 2,56-2,66g/cm3 depending on chips' type. Fig.3 shows relative density of billets depending on the chips type. Relative density represents ratio between measured density of billet and theoretical density of aluminium. It can be concluded that the lower the chip's average size and simpler the chip's shape, the higher density that can be obtained.

*Table 2– Billets obtained by 245 kN compression force*

| Type A | Type B | Container for chips |
|---|---|---|
|  |  |  |
| density: 2,67 g/cm$^3$ | density: 2,66 g/cm$^3$ | |
| | | |
| Type C | Type D | Punch and die |
|  |  |  |
| density: 2,58 g/cm$^3$ | density: 2,57 g/cm$^3$ | |

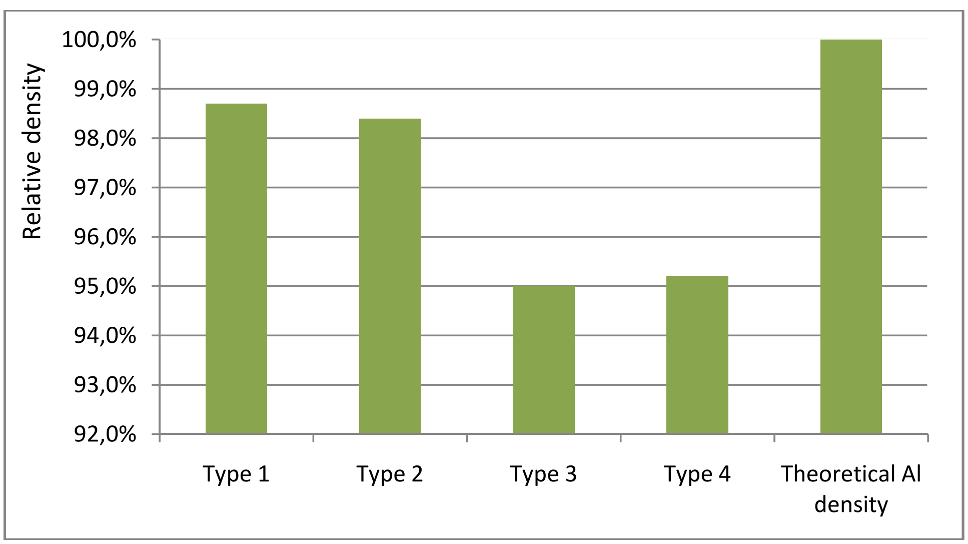



***Fig. 3 – Relative densities of obtained billets***

### 3.2.2 Cold compression with 98kN force

Cold compression with 98 kN force was performed in order to verify if satisfactory density and material strength could be obtained with lower normal pressures. Influence of chips' type on density was not observed as all chips types were mixed together. Obtained billets were ϕ32x7mm in size with total mass of cca.11 grams.

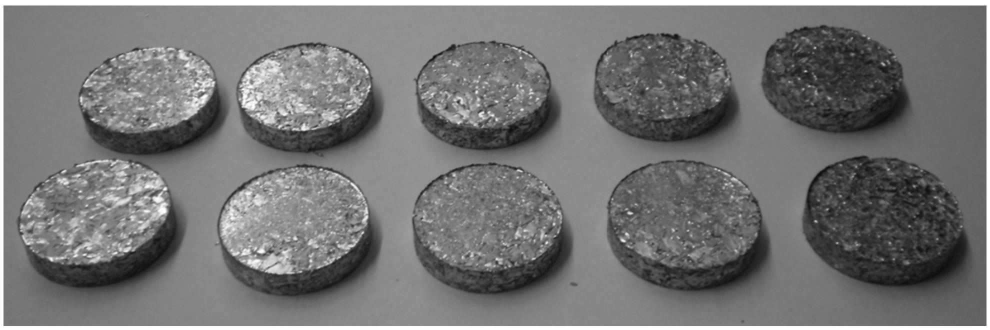


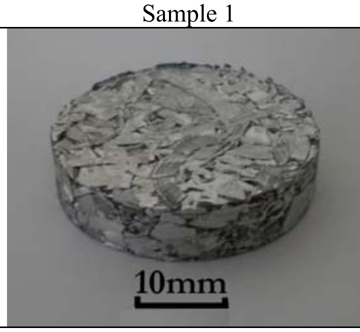
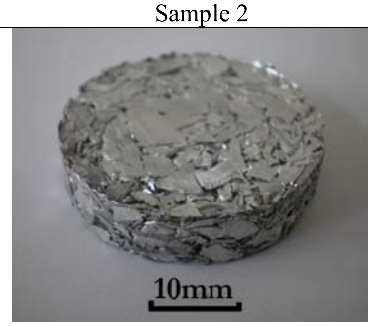
***Fig. 4*** *– Billets compacted with 98kN force*

Average densities of these billets were around 2,2 g/cm$^3$, which is about 81% of theoretical density of aluminium (2,7g/cm$^3$).

### 3.2.3 Cold compression with 8,8kN force

Cold compression was also performed with extremely low force of 8,8kN which is approx. 900 kg. Due to very low pressures on chips, a low relative density (around 65%) was obtained (Table 3).

*Table 3– Billets obtained by 8,8kN compression force*

| Sample 1 | Sample 2 |
| --- | --- |
|   |   |
| Mass: 10,60 g | Mass: 10,43 g |
| Dimensions: ϕ32,12x7,22mm | Dimensions: ϕ32,05x7,19mm |
| Density: 1,81 g/cm$^3$ | Density: 1,80 g/cm$^3$ |
| Relative density: 67,14% | Relative density: 66,83% |

### 3.2.4 Cold compression comparison

Fig. 5 provides comparison of different compaction forces and their influence on billets' final densities. As expected, billets compressed with 245kN force exhibit highest densities (cca. 98%), while billets compressed with 98kN and 8.8kN exhibit 80% and 65%, retrospectively.

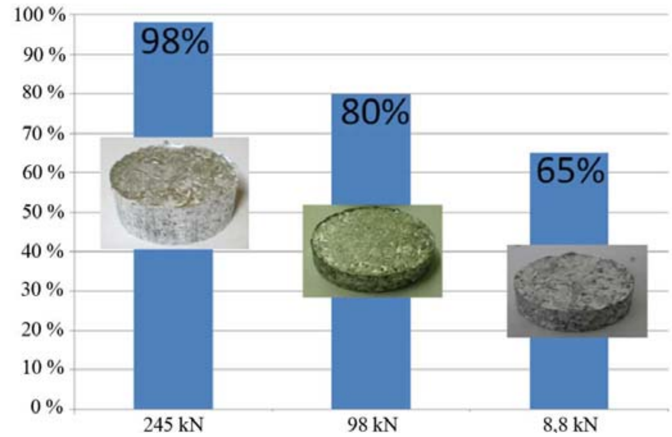



***Fig. 5 - Influence of pressure on billets relative density***

### 3.2.5 Backward extrusion and free upsetting

Backward extrusion on compressed A-type billets was performed in order to test the intensity of chips consolidation. Billets were extruded in the same die used for compression with two different punches (ϕ24.2 mm and ϕ20.8 mm). During backward extrusion deterioration of the outer wall of the billet occurred. Backward extrusion test showed that ships in A-type specimens were not fully consolidated and that further enhancement of chips bonding is needed (Fig. 6).

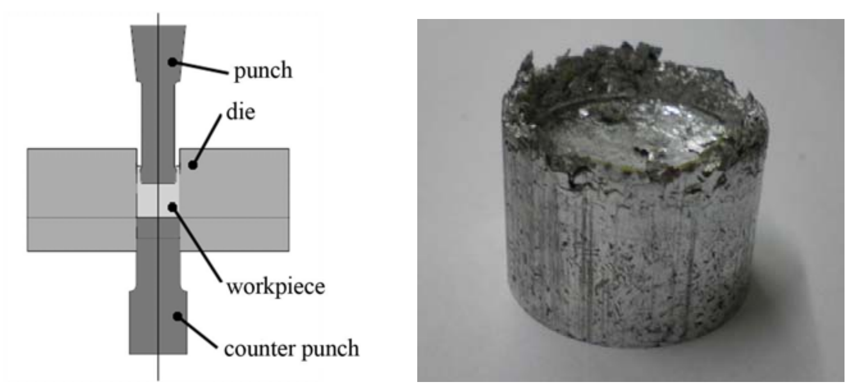



***Fig. 6 – Schematics of backward extrusion and workpiece after deformation***

Free upsetting of A-type billets was also conducted to investigate material behaviour during this process. In Fig. 7 photo of upset specimen and load – stroke curve are presented. Although integrity of the specimen during compression remained, deterioration of the outer surface also occurred, similar as in backward extrusion.

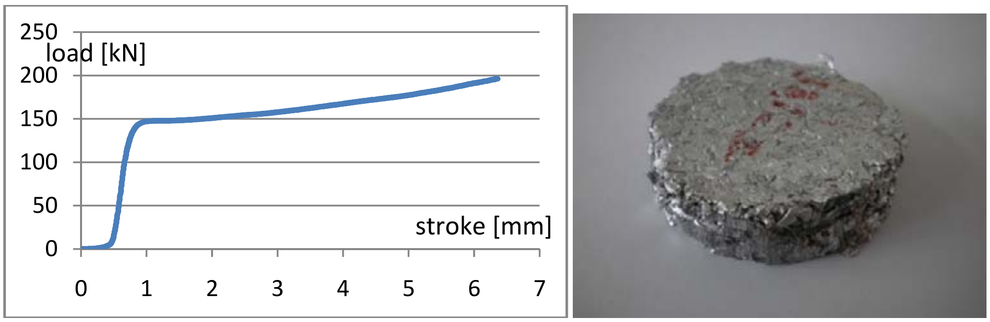



***Fig. 7 – Load–stroke diagram and workpiece after free upsetting***

Backward extrusion and free upsetting of specimens showed that further material processing is essential in order to obtain material that performs similar to the one obtained by conventional recycling. Therefore, workpiece material has to undergo higher shear deformations, hydrostatic pressures and perhaps preheating. One of the solutions may be found in severe plastic deformations techniques.

## 4. SEVERE PLASTIC DEFORMATION

Severe plastic deformation (SPD) is a technique in which material is processed by very high deformation values, whilst change in workpiece's shape and size does not take place. The first principles of SPD were developed at Harvard University in 1930s by Professor Percy Williams Bridgman. Specific tooling design enables very high hydrostatic pressures and shear stresses. Extremely high deformations in material cause division of grains. However, this phenomenon is scientifically not yet completely clarified. High hydrostatic pressures, on the other hand, preserve workpiece's integrity and disable crack occurrence.
Relation between grain size and material strength is well known and established by Hall-Petch:

$$\sigma_y = \sigma_o + \frac{k_y}{\sqrt{d}}$$

where$\sigma_y$ is material's flow stress, $\sigma_0$ is a constant, $k_v$ is strengthening coefficient and $d$ is average grain diameter.
One of the most important advantages of SPD is that material can be processed several times through the same tool, as the initial and final shape of workpiece are identical (or at least very similar). Although, SPD techniques are most commonly used in material's grain refinement, they can also be employed in consolidation of chips. Therefore, previously compacted billets could be processed with one or several of the SPD methods at room or elevated temperatures. High deformation will cause more severe material bonding and hydrostatic pressure will ensure that billets do not disintegrate during processing.

The most important SPD methods are:
- Equal channel angular pressing (ECAP)
- Twist extrusion (TW)
- High pressure torsion

## 4.1 Equal channel angular pressing (ECAP)

ECAP has been developed by Segal in the 1980s and there are several variants of this method. The most common variant is presented in Fig. 8. A rectangular or cylindrical workpiece is placed in "L"-shape tool and extruded by the punch. Final part shape slightly differs from initial, as friction on the lower workpiece surface is higher. This phenomenon can be prevented by adding a counter punch on the other opening of the die, which provides backpressure.

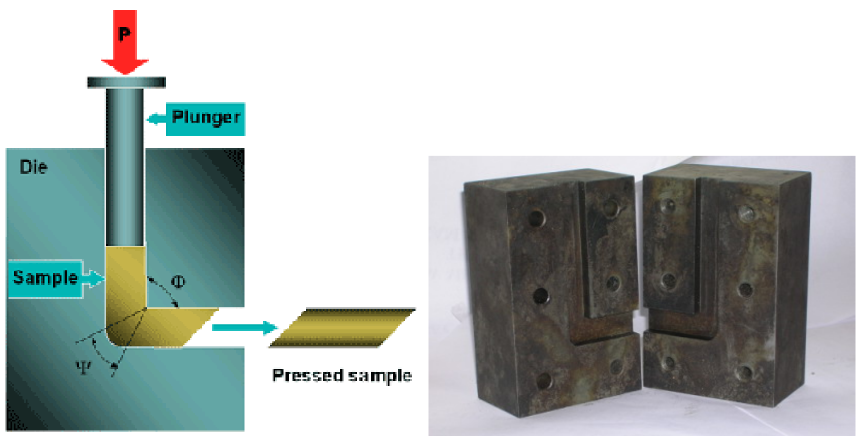



***Fig. 8 – ECAP process (left) and tooling (right)[6], [7]***

In another variant of die design, angle Φ can be smaller than 90°, which enables processing of more brittle materials, but however, reduces the amount of material deformation.
The main advantages of ECAP method:
- the possibility to process one workpiece unlimited number of times in one tool and to achieve very high deformation values
- deformation is homogenous in whole workpiece volume
- large workpieces can be processed
- deformation zone is limited to small volume, which reduces the necessity for large forces and pressures
- process can be conducted at room temperature.

## 4.2 Twist extrusion (TE)

In Twist extrusion (Fig. 9), workpiece is extruded through a complex designed die, where entry and exit cross sections are identical, but turned for a specific angle β (usually β = 90°). Die, due to its large stiffness and complex design, provides high hydrostatic pressures and shear deformations, which enable grain refinement and therefore increase in material strength.Like in ECAP, TW also enables several extrusions of the same workpiece in the same die, as material's initial and final shape and dimensions are the same.

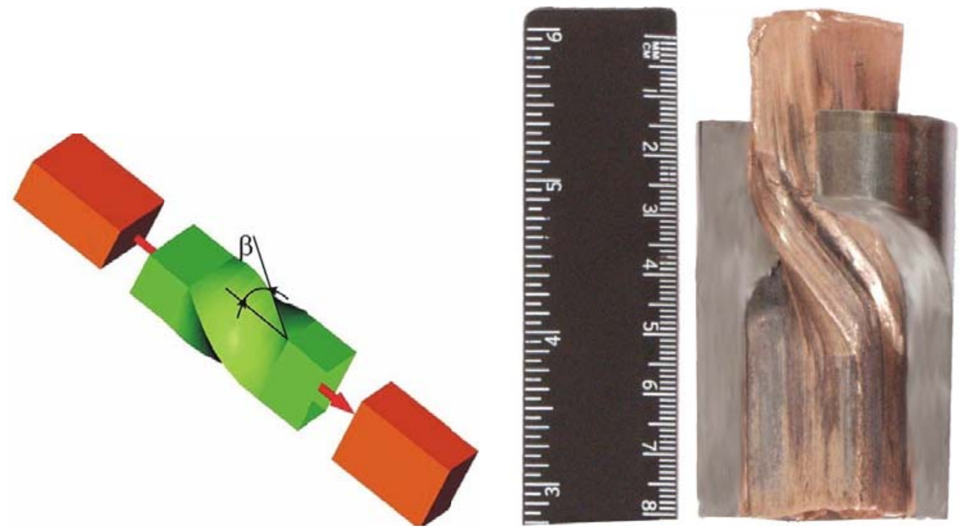



***Fig. 9 – Twist extrusion process and photo of the workpiece during TE[8]***

The most important asset of TE is the possibility to produce a large number of different cross sections, as well as parts with holes (Fig. 10). Drawback of TE is the complex die design and inhomogeneous deformations in the workpiece (deformation is oriented in one direction).

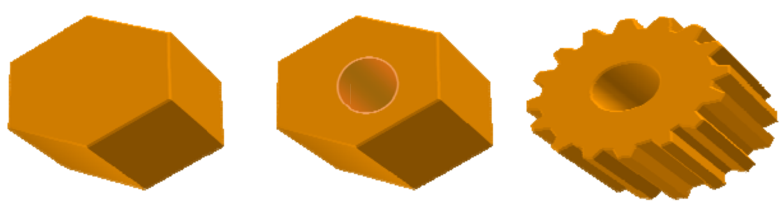


***Fig. 10 – Part examples that can be strengthened with twist extrusion[8]***

There are other variants and combinations of TE, such as: hidromechanical TE, backpressure TE, TE drawing, high velocity TE etc.

## 4.3 High pressure torsion (HTP)

In HTP, cylinder-shaped workpiece is placed between upper and lower tool. Machine applies forces (F) on both tools in opposite directions (Fig. 11). Rotation of the lower tool and vertical forces induce high shear deformations and hydrostatic pressure in workpiece. As there is no space for material flow, shape of the workpiece remains constant.

The main benefits of HPT are:

- simple tooling construction
- the possibility for achieving large deformations
- the possibility to process brittle and hard materials
- simple control of hydrostatic pressure and shear deformation by setting of vertical forces and rotation velocity.

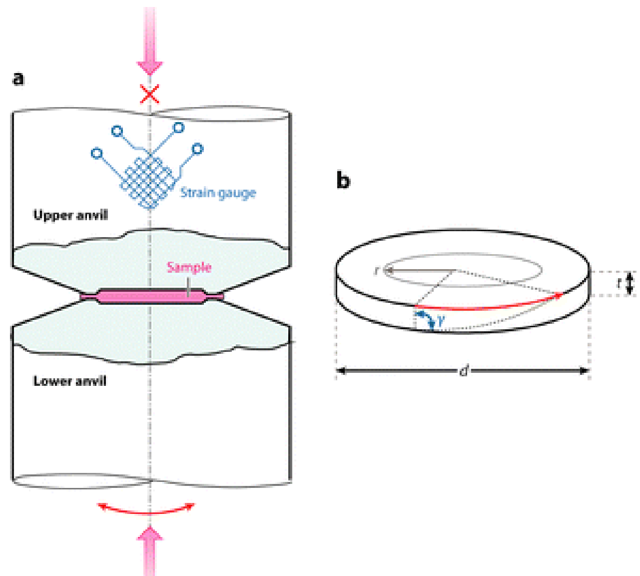



***Fig. 11 – Schematics of high pressure torsion (HTP)[9]***

However, HPT has several drawbacks, such as:

- limit in workpiece size (due to a necessity for high hydrostatic pressures)
- only cylindrical-shaped workpieces can be processed
- unequal deformation values through the material's volume, due to different rotation velocities on the cross section.

## 5. CONCLUDING REMARKS

Solid state recycling of aluminium chips into solid billets has a number of advantages over conventional recycling. This process enables material and energy savings and it is more eco-friendly as no remeltingtakes place.However, solid state recycling has application only in processes where no material mixing is performed and where cutting waste is simply sorted (the best example is in mass machining).

This paper elaborates cold compression process of Al-alloy chips. The influence of chips' shape and size as well as compression forces on final billets densities was investigated. It was concluded that smaller chips size lead to higher billets densities for constant pressure. Compression force proved to be very important factor in proper chips solidification, as billets compressed with lower forces exhibited small final densities.

Final experimental investigations (backward extrusion and free upsetting) proved that in order to obtain good mechanical properties of compressed billets further processing of the material is needed. Further research would consider employing severe plastic deformation methods in order to enhance material properties. At the end a brief overview of severe plastic deformation methods is given.

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# DIREKTNO RECIKLIRANJE ALUMINIJUMSKE STRUGOTINE PUTEM HLADNOG SABIJANJA

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## REZIME

*Direktna reciklaža strugotine aluminijuma u kompaktne uzorke ima nekoliko značajnih prednosti u odnosu na konvencionalnu reciklažu. U direktnoj reciklaži, otpadci nakon odrade se deformišu visokim pritiscima i eventualno povišenim temperaturama kako bi se dobio nov, kompaktni materijal. Ovaj proces omogućava uštedu kako u materijalu tako i u energiji i omogućava veću zaštitu životne okoline jer nema procesa pretopljavanja. Ipak, direktna reciklaža ima primenu samo u procesima gde ne dolazi do mešanja materijala i gde se otpadci (npr. strugotina) tokom obrade jednostavno daju prikupiti.*
*U ovom radu izvršena je analiza procesa hladnog sabijanja u zatvorenom kalupu strugotine od AlMgSi1 legure aluminijuma. Vršeno je ispitivanje uticaja tipa i veličine strugotine, kao i sile sabijanja na krajne gustine kompaktnih uzoraka. Zaključeno je da manja i jednostavnija strugotina rezultira u većim krajnim gustinama.*
*Nad sabijenim uzorcima izvršene su i operacije suprotnosmernog istiskivanja i slobodnog sabijanja kako bi se dobio uvid u kvalitet spoja strugotine. Iako su uzorci pokazali zavidnu kompaktnost, na spoljnoj površini kod slobodnog sabijanja i na gornjoj površini kod istiskivanja došlo je do razdvajanja strugotine. Na kraju rada dat je prikaz tehnika koje uključuju veoma velike deformacije i hidrostatičke pritiske kako bi se poboljšale mehaničke osobine sabijenih uzoraka.*
***Ključne reči: d****irektna reciklaža, sabijanje strugotine, sabijanje u zatvorenom kalupu, strugotina aluminijuma*