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Evolutionary in Solid State Recycling Techniques of Aluminium: A review

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Abstract

This paper provides an intensive review on past and current research works in solid state recycling of aluminium and its alloys. The review relates the extrudates quality of the solid state recycled aluminium to certain aspects noted as chips preparation, reinforced materials addition, die geometry, processing parameters, and performance of miscellaneous solid state recycling techniques. Finally, concluding remarks underline challenges for aluminium recycling by the solid state and also highlight the potential future work on making the method as a promising alternative for sustainable manufacturing and hence technologically feasible for industrial implementation.

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Keywords: solid state recycling; aluminium;

1. Introduction

The benefits of solid state or direct recycling of aluminium are perceived important by researchers. It can reduce fund for environmental protection and better energy consumption than the conventional recycling by remelting can offer. In addition, significant amount of carbon footprint also can be cut down. In secondary aluminium production, energy about 10 GJ/ton of the material is needed, making up about 5-10 % of the energy in the primary aluminium output, and the trend is increasing for the subsequent years [1]. In 2030, a recycling rate of 50% is expected [2]. The figures indicate that demand for energy in secondary aluminium processing through remelting is increased significantly. Although there have been several successful efforts to improve energy efficiency of melting furnaces since the 1980s, nevertheless the energy consumption for secondary aluminium production can still go up to 20 GJ/ton depending on the condition of aluminium scrap, production facilities and processes [3, 4].

In the case for aluminium chips, the conventional recycling method was unfavourable due to a significant metal loss. Low density of the compacted chips enhances losses through oxidation. There are further losses on each stages of subsequent processing caused ultimately no more than 54% of the metal is recovered during conventional recycling by melting [5]. For instance, conventional recycling of aluminium turnings caused to approximately 45% losses in the metal [6]. Those losses impacted to costs rising in labour, energy and expenditures for environmental protection which subsequently increase the general cost of the process.

The direct recycling of aluminium fewer in steps involved, higher recovery efficiency and capable of enhancing material properties to the great extent [6, 7]. These advantages attracted more and more researchers to further explore the potential of direct recycling to manufacture the end products. However, despite great advantages of the direct recycling, its adoption by industry has been very sluggish so far due to notion that the property improvement is still uncertain.

It is very important to discuss and highlight the various factors in making solid state recycling of aluminium successful and practicable. This paper reviews evolutionary in the solid state recycling for aluminium which together demonstrates how different factors and advancement in the techniques affect property enhancement of the extruded profiles. Finally, some challenges to be overcome in the solid state recycling technique are also discussed in the concluding remarks.

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2. Experimental studies of solid state recycling

A number of experimental works have been attempted to optimise quality of the extruded profiles through the solid state recycling. The influence can be due to the material-based parameters such as chip constituents including types of chip, reinforced material, and their morphology. While for the process-based factors, method of chips cleaning, compaction strategy (temperature and force applied), heat treatment and types of plastic working method include the process parameters were the critical aspects to be taken care. As for the geometry-based parameter, the die design determines the level of strain and pressure imposed to promote the inter-chip welding quality during the deformation.

2.1. Effects of chips preparation

The quality of the recycled chip-based billet produced by plastic working is significantly affected by the way chips are prepared for consolidation at the early stage. Common factors to influence the chips preparation are pressure and duration of pressing, method of recycling, chips types, and their morphology.

Fogagnolo [8] found the quality difference between the extruded material from the cold and hot pressed chips is not significant. An increase in the pressing pressure or pressing time produces higher degrees of consolidation. The direct powder metallurgy method was also attempted in direct aluminum recycling [9]. Heat and a low pressure was used on granulated aluminium to soften the particles and reduce the springback action. The results showed that the method was inferior by 9-12% in green density, 2-13% in compressive strength, and 18-29% in Brinell hardness as compared to the commercial aluminium powder method pressed at 360 MPa.

Distinct forms of aluminium scraps was reported used in solid state recycling. The 1050 aluminium alloy in the pin forms was mixed by Guley [1] with 6060 aluminium alloy chips. Findings revealed that no optical difference can be seen between the extruded profiles and the as-cast billets microstructures. The extruded profiles of the mixture of AA6060 chips with AA1050 pins have an intermediate character between AA6060 as cast billet and AA1050 source material in tensile test results.

Tekkaya [10] investigated the properties, yield behaviour, microstructure and drilling behaviour of extrudates by direct hot extrusion of re-use of aluminium AA-6060 alloy chips produced by milling and turning operations with different sizes and shapes. The mechanical properties of the seam welds surrounding the chips are nearly as good as the properties of the base material. The yield strength of extruded chips is comparable to solid billet extrudates. The chips of the drilling process tend to have a reduced in total size for profiles extruded from recycled chips.

In overall, the quality of the chip-based extrudates is affected by the chips morphology if insufficient stress and strain are applied during the forming process. Therefore, minimum stress, strain, and temperature conditions are needed for creating a metallic bonding regardless of different chip geometries. In economic direct recycling, the cold pressing and hot extrusion route is more preferable then the hot pressing and hot extrusion route due to the cost benefit ratio as recommended by [8].

2.2. Effects of reinforcing phase and mixture of different aluminium alloys

The effects of adding reinforced materials in the consolidated chips were noticeable in terms of their mechanical and physical properties. The fabrication of composites from Al, AlCu4-alloy and AlMg2-alloy granulated chips with different amounts of tungsten powder addition (≈ 80 mesh size) was proposed by [7, 11]. Composites with low porosity, good diffusion bonds and the relative density exceeding 98% were obtained with tungsten powder addition. The heat treatments on Al and AlCu4-base composites caused the strength to increase meanwhile the plastic properties is decreased.

The direct conversion of granulated aluminium and its alloys chips ($AlMg_2$ and $AlCu_4$) into finished products through hot extrusion process were developed by [5, 12, 13]. The reinforcing phases used were aluminium oxide, tungsten, carbon, ferro-chromium and aluminium bronze comminuted chips. The findings reveal that the relative densities of the composites after hot extrusion are almost identical (over 98%) as those of solid materials made from aluminium powder with the hardening additions. A tungsten-powder addition and the aluminium oxides formed during the process, improved the strength and hardness properties. According to [8], the oxides content when introducing Al_2O_3 hardening phase in recycling aluminium alloy chips caused the higher UTS of the recycled composite material compared with the original composite.

Carbon addition results in discontinuities in the structure of the composite and thus impairs the strength and plastic properties of the composite. For ferro-chromium composite, a smaller fraction of granulated chips results a better mechanical properties due to uniform distribution of the ferro-chromium phase in the aluminium matrix. The effect of different presintering medium neither in air nor vacuum was negligible. The fractures strain of the composites increases with temperature and decreases with ferro-chromium content.

Composites with comminuted aluminium-bronze chips found to produce good tribological properties. The strength and plastic properties have meet the requirements for bearing materials [12]. Bearing composites were also developed by [14, 15] through cold compaction and hot extrusion. Hot extrusion did improve the density to above 95% of the theoretical density of the materials and hard phases were created. The weak bonding could deteriorate the wear of composites. To improve the bonding, heat treatment of composites after extrusion was suggested.

Researchers [12-14] inferred that aluminium-based composites with comminuted aluminium-bronze reinforcing phase produced good tribological properties while [5, 12, 13, 15] concluded that the reinforcing phase with uniform distribution and good bonding composites can be obtained via compaction and hot extrusion.

Mixing different chips of AA6060, AA6082 and AA7075 was investigated by [16] which then compacted and hot extruded. He found joining occurred amongst alloys. The mechanical properties of the profiles are 5 to 10 % lower than those of cast billets. Despite, the extrudates with mixed chips had increased strength of the original chips. Nevertheless when the mixed alloys strength is increased, a proper extrusion parameters need to be selected to prevent the surface defects.

The possibility of adding SiC particles into distinct chip geometry of aluminium 6060 alloy chips was tested by [10]. The trials failed because the particles caused destruction in many spots of the extruded profiles surface and the surface was rough. The tensile tests revealed a reduction in flow stress which reduced the strength. Mindivan [17] attempted to produce aluminium matrix composite by the direct conversion of 6082 aluminium alloy chips mixed with fly ash. Addition of the fly ash increased considerably the hardness and the alloy exhibited superior wear than those conventionally produced.

In conclusion, alloying elements either from recyclable wastes or original forms can be mixed or sometimes alloyed with the recycled aluminium chips as an additive for strengthening purposes. Heat treatment applied after extrusion could improves tribological properties, strength and hardness of the composites by increasing diffusion bonding and creation of new phases.

2.3. Effects of die geometry

The die geometry plays an enormous role to ensure a sound inter-particle chips bonding in the extrusion die is achievable. A proper die design will guarantee sufficient billet densification, chip bonding and the evolution of a desired microstructure [5].

The extruded profiles were reported successful produced by a modified four turn equal channel angular pressing die (iECAP die) and a porthole die on AA6060 aluminium chips [18]. The results indicate no voids encountered on the profiles from both dies. The chip-based billets extruded through the iECAP showed superior hardness and tensile strength then the cast billets extruded by the flat-face die.

The performance of the flat-face and porthole dies in direct recycling of AA6060 chips were also compared [19]. By porthole die, the chips welding and the ductility is 80% higher than the flat-face die was obtained. Meanwhile for the microhardness and the yield strength, the porthole die performed lower than its rival. The microstructure of the sample extruded by the porthole die exhibited an equiaxed grains and counted almost twice than the grain size revealed by the flat-face die sample before the heat treatment.

The effects of different routes of chip consolidation and dies design over mechanical properties are done by [20]. The AA6060 aluminium alloy chips were compacted into billets using three techniques known as traditional compaction in one stroke, multi-layer compaction and front-pad, adapted from powder extrusion. The three types of extrusion dies used were the flat-face die (R=8.6, v=1mm/s), the modified porthole die (R=8.6, v=1mm/s) and ECAP die (R=8.6 & v=1 mm/s; R=8.6 & v=6 mm/s; R=34 & 1 mm/s).

The multi-layer compaction results in better density chip-based billets and at low extrusion ratio of R=8.6, the combination of cold compaction and hot extrusion via flat-face die does not guarantee sufficient chip bonding. The application of porthole and ECAP dies provide a sufficient chip bonding and better ductility compared to the cast billet extruded. The mechanical properties in particular tensile strength did not change much between multi-layer and single-layer compaction. Higher ram speed or extrusion ratio for the ECAP die led to a slight decrease on strength and ductility of the extrudates which due to the high generated temperature.

To sum up, the mechanical properties of the extruded profiles can be improved by optimizing the die design for extrusion. For the porthole die, the distribution of homogeneous oxide layers, dynamic recrystallization, high heat and high shear force experienced by the chips were the main causes of the great chips consolidation. While for the ECAP die, excellent mechanical properties of the extruded profiles were principally due to the fine uniform grains in all microstructure.

2.4. Performance of miscellaneous methods in direct recycling process

i. Extrusion and rolling method

Suzuki [21] proposed method of aluminium chips recycling by hot extrusion and hot rolling with T6 heat treatment. The hot rolling was performed in two conditions: normal and differential speed rolling (DSR). The tensile strength of the recycled materials obtained after 580K was slightly superior to non-recycled material (NR). In strength and elongation, the DSR-based consolidated chips is outstanding than the normal-based rolling and obviously at larger rolling reduction per pass. The smaller grain diameters obtained for the recycled materials increased ductility for subsequent forming processes. In corrosion resistance, the both recycled and NR materials are comparable.

The possibility of recycling Al–Si alloy machining swarf (AC4CH) using cold extrusion and a subsequent cold rolling process has been explored [22]. The produced specimens were straight without warping. No grain boundaries were observed in the rolling-recycled material probably due to severe cold working. The recycled materials had higher strengths than the original AC4CH ingot. The combination of extrusion and rolling on the recycled material result in considerable strength and density improvement then recycled by the single extrusion.

Allwood [23] investigated recycling of aluminium 1050A-H14 scrap by compaction, flat-rolling and forwards extrusion, all are performed separately. The findings show chips bonding will increase with the increase of the extrusion ratio while lubricant applied does not show significant reduction in ram force. The deformed sheet metal was unstable with extensive edge cracking and a little bonding occurred.

ii. Equal channel angular pressing (ECAP) method

The ECAP method in direct recycling was performed on the automotive aluminium scraps as an alternative technique by [24, 25]. The effects of heat and chemical cleaning methods on the chips were also studied. The findings show hot tearing on all surfaces after both l pass and 3 passes. No metallic bonding was found between particles that experienced by the only cold compaction. A fully dense solid bar was obtained from the aluminium particles by performing only one deformation pass at 450°C. Using thermal methods, the lubricant and acetone on aluminium turnings scrap can be decomposed successfully at temperature around 290°C. The ECAPed specimens show hot tearing after 2 passes and impurities are also encountered [25].

iii. Conform method

The recycling viability of aluminium trimmings by a conform process directly into extruded products has been tested [6]. The process successfully produced the wire, rod, bars, solid shapes and tubes from the trimmings.

The historical developments pertaining to the experimental study of aluminium and its alloys under the solid state recycling with the details aspect of study are chronological tabulated in Table 1.

Table 1. Evolutionary in experimental study of direct recycling of aluminium and its alloys.

Author/s	Year	Key experimental aspects
[6]	1991	▪ Performed recycling of aluminium trimmings by conform process directly into extruded products.
[7]	1996	▪ Fabricated composites from Al and AlCu4 chips with addition of different tungsten powder amount by hot extrusion and investigated the effects of heat treatment by means of ageing at 170°C and solution treatment at 510°C for 1 hour on yield strength and hardness.
[11]	1998	▪ Studied the effects of small addition of tungsten powder of 80 mesh in production of composites Al and AlMg2-alloy granulated chips (sized < 4mm) by hot extrusion.
[5, 12, 13]	2000/1999/ 2001	▪ Developed the direct conversion of granulated aluminium and its alloys chips (AlMg2 and AlCu4) into finished products through compaction, sintering and hot extrusion processes. The reinforcing phases used were aluminium oxide, tungsten, carbon, ferro-chromium and aluminium bronze comminuted chips.
[14, 15]	2000/2006	▪ Developed bearing composites through cold compaction and hot extrusion. The comminuted aluminium chips were used as matrix, while aluminium-bronze chips with 8%, 12% and 13% Al content were used as reinforcement particles.
[8]	2003	▪ Employed direct recycling aluminium alloy chips reinforced with Al_2O_3 by cold/ hot pressing without milling step followed by hot extrusion.
[9]	2003	▪ Recycled aluminium scrap by a direct technique of powder metallurgy method.
[26]	2005	▪ Studied the influences of chips characteristics and extrusion conditions on the properties of a 6061 aluminium alloy.
[23]	2005	▪ Performed recycling of aluminium scrap by compaction + flat-rolling (39%, 45%, 52% and 58% reduction) and compaction + forwards extrusion separately.
[21]	2007	▪ Performed recycling cutting chips 6061 aluminium alloy by hot extrusion and hot rolling with T6 heat treatment.
[16]	2008	▪ Investigated the recycling of AA6060, AA6082 and AA7075 aluminium chips and their mixtures through compaction and hot extrusion.
[24, 25]	2009/2010	▪ Implemented technique of equal channel angular pressing (ECAP) in direct recycling of automotive aluminium scrap. The effectiveness of degreasing methods over aluminium alloy (AA6060) turnings also investigated.
[10]	2009	▪ Investigated the effects of chips sizes and shapes on the mechanical properties, microstructure and cutting behaviour of extrudates by direct hot extrusion of re-use of aluminium AA-6060 alloy chips.
[17]	2009	▪ Attempted to produce aluminium matrix composite by the direct conversion of 6082 Al alloy machining chips mixed with fly ash.
[1]	2010	▪ Mixed 1050 aluminium alloy in the pins forms with 6060 aluminium alloy chips resulting from a turning operation, cold compacted into billets and hot extruded at 500°C.
[27]	2010	▪ Investigated the effects of extrusion ratio on hot extrusion of recycled AZ91D magnesium alloy scraps.
[22]	2011	▪ Tested the possibility of recycling Al–Si alloy machining swarf (AC4CH) by cold extrusion and a subsequent cold rolling process.
[28]	2011	▪ Investigated the effect of the extrusion ratio (ER) and material flow by flat-face die and porthole die on the mechanical properties of solid state recycled aluminium from 6060 aluminium chips by hot extrusion.
[18]	2012	▪ Succeeded to produce profiles extruded from aluminium chips AA6060 through a modified four turn equal channel angular pressing tool (iECAP die). The performances were compared with porthole die and flat-face die.
[20]	2012	▪ Studied the effects of different routes of AA6060 chips consolidation and dies design over mechanical properties. The three types of extrusion dies used were the flat-face die, the modified porthole die and ECAP die.
[19]	2013	▪ Extruded AA6060 chips through a flat-face and a porthole die to produce solid rectangular profiles.

Table 2. Summary of process parameters employed in solid state recycling of aluminium chips and its alloys.

Key processing parameters	Researcher/s
A: Billet Temperature (°C)	
PT[a](550, 3hrs)	[28]
PT(500, 50min)	[8]
PT(500, 2hrs)	[13, 19]
PT(550, 6hrs)	[1, 16, 18]
ST[b](550, 2hrs)	[5]
PT(450, 20min)	[27]
PT(500 / 550)	[10] / [20]
PT(550, 15min)	[12]
B: Forming Temperature (°C)	
ET[c](450)	[1, 10, 16, 18-20, 28]
ET(500)	[7, 8, 11, 12, 15]
ET(550)	[5, 12, 18]
ECAPT[d](450)	[24]
ET(520)	[14]
C: Compaction Force	
400-500 kN	[20, 28]
25 MPa	[23]
625 MPa	[25]

400 MPa	[14, 15]
650 & 700 MPa	[8]
210 MPa	[7, 11, 12]
60 kN	[1, 10, 16]
303 MPa	[22]
200 & 360 MPa	[9]
D: Extrusion Ratio	
6:1	[22]
2:1	[23]
4:1	[22, 23]
68:1 & 10:1	[28]
34:1	[19, 20, 28]
11:1 & 40:1	[27]
8.6:1 & 8.7:1	[18, 20]
6.25:1	[8, 12]
25:1	[8, 27]
34.2:1	[1, 10]
E: Extrusion Speed (mm/s)	
1 mm/s	[1, 10, 16, 18-20]
2 mm/s	[22]
6 mm/s	[20]
10 mm/s	[7, 11, 12, 14]
20 mm/s	[28]
F: Type of Lubricant	
Graffito	[8]
Zinc stearate with graphite	[13, 15]
MoS2	[23]
G: Reinforced Material	
Tungsten	[7, 11, 12]
Graphite	[12]
Aluminium bronze	[12]
Ferro-chromium	[5]
SiC	[10]
Alumina	[8]
H: Heat Treatment	
Annealing (1h, 300°C)	[22]
Chips annealing (60-110 min, 490-505°C)	[9]
Quenching at 40°C	[9]
Annealing (7hrs, 545°C)	[15]
I: Die Angle	
20° & 45°	[23]

Note: [a]PT (preheating temperature), [b]ST (sintering temperature), [c]ET (extrusion temperature), [d]ECAPT (ECAP temperature)

2.5. Effects of processing parameters

The influence of process parameters on aluminium chips bonding is huge. The effects of chip characteristics, extrusion conditions as well as types of the reinforcement on the extruded profiles are very important [10, 26]. Researchers [11, 12] concluded that the significant factors affecting the chips bonding are contributed by: (1) the amount, form and size of the reinforcing phase, (2) the degree of fragmentation of the aluminium-alloy chips, (3) the pre-molding parameters, (4) the shape of the extruding dies, (5) the degree of extrusion pressing, (6) the lubrication method, (7) the lubricants used, and (8) the temperature and the rate of extrusion.

In addition, Gronostajski [11] further elaborates that the good diffusion bonds and very low porosity of extruded composites are attainable at high extrusion temperature. The combination of high heat and low extrusion speed enables the matrix material to flow plastically into pores and voids, and thus allows longer inter-particles diffusion. The geometry of the chips is an important factor in the chip compaction strategy to achieve uniform density in pre-compaction [19]. Meanwhile Tekkaya [10] proved that the influence of chip morphology on the tensile properties is negligible when the porthole dies with the extrusion ratio, $R \geq 30$ are used.

Guley [28] in his study found though the flat-face die, an extrusion ratio (ER) of 10 did not guarantee sufficient chip bonding. While at the higher extrusion ratio, the extruded profiles were found to gain superior strength and ductility. He subsequently confirmed that by the porthole die, at $ER \approx 10$, the profiles strength was equivalent to the profiles extruded by the flat-face die at $ER \approx 68$ and in ductility, the porthole die performed better. Later, study by Fogagnolo [8] led to findings in lower extrusion ratio (ER = 6.25), hot press and hot extrusion is needed to obtain good consolidated chips. At high extrusion ratio, he commented that the effects of heat are negligible for chips consolidation.

To sum up, it is found that at high extrusion ratio, excessive strain, high compressive pressure and high shear forces can be imposed on the extruded profiles to successfully breaking the oxide layers surrounding the chip surfaces. It is then caused virgin metal to metal be in contact to diffuse together for better chips joining. A high extrusion ratio also responsible for the strength and ductility improvement of the chip-based profiles [27]. The process parameters employed in the direct recycling of aluminium chips is summarized in Table 2.

3. Concluding remarks

Numerous studies have been carried out to explore the practical aspect of direct recycling of aluminium and its alloys since the early 1990's. Going through thoroughly the literature, it is found that the direct recycling is possible for aluminium chips. In terms of the technological feasibility, endless efforts are still needed to convince the industry on this technique. Some challenges in this area are addressed here:

- Obvious challenges for the solid state recycling may come from heterogeneous characteristic owned by the chips [25]. Eventhough the different alloy mixtures can improve strength, the inverse bad effect on the surface quality will tend to emerge [16]. It is therefore, an investigation on the effects of different alloy mixtures on the mechanical and physical properties should to be carried out thoroughly. A proper extrusion parameters to be adapted is also becoming a primary concern in this aspect to ensure the subsequent processes are not hindered.
- The time consuming activities during selection, preparation of the chips, setting machine tools and selection of the process parameters should to be reduced tremendously for industrial viability.
- The analytical approach and design of experiment method can be proposed to optimize the process parameters so that the welding quality and the microstructure evolution of the chip-based products can be determined in advanced by finite element analysis (FEA) simulation for obtaining products with low cost and better quality.
- The effects of oxidation on the hot extruded aluminium require further investigation because oxide layers impairs the inter-particle chips bonding.
- Although it may reduce strength to gain a greater chips bonding in the subsequent operations, optimization in

annealing of aluminium chips still need further improvement because the process is time consuming.

- In most of the experimentation, the tensile tests were executed only in the extrusion direction. Additional tensile tests must be executed at the transverse direction to analyse the effect of material anisotropy [28].
- The industry faces a huge challenge to produce significantly fine particles from the recycled aluminium. A new machine with a sophisticated milling cutter should be developed to overcome this problem.
- ECAP is found suitable as an alternative in recycling of machining scraps. Nevertheless an inhomogeneous property of the ECAPed chip-based extrudates results in challenges for the process [25]. Hence, further work could be focused on the combination of hot compaction, hot ECAP and extrusion to clarify the influence of the integrated process on the mechanical properties of the finished products.

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References

[1] Güley V, Khalifa NB, Tekkaya AE. Direct recycling of 1050 aluminum alloy scrap material mixed with 6060 aluminum alloy chips by hot extrusion. International Journal of Material Forming. 2010;3:853-6.

[2] Schwarz H. Aluminum production and energy. Encyclopedia of energy. 2004:81-95.

[3] Macintosh WH. Induction furnaces for melting secondary aluminium. Conservation & Recycling. 1983;6:41-8.

[4] Butterwick L, Smith G. Aluminium recovery from consumer waste-I. Technology review. Conservation & recycling. 1986;9:281-92.

[5] Gronostajski J, Marciniak H, Matuszak A. New methods of aluminium and aluminium-alloy chips recycling. Journal of Materials Processing Technology. 2000;106:34-9.

[6] Lazzaro G, Atzori C. Recycling of aluminum trimmings by conform process. Minerals, Metals & Materials SOC(TMS), Warrendale, PA,(USA). 1991:1379-84.

[7] Gronostajski JZ, Marciniak H, Matuszak A. Production of composites on the base of AlCu4 alloy chips. Journal of Materials Processing Technology. 1996;60:719-22.

[8] Fogagnolo JB, E. M. Ruiz-Navas, M. A. Simon, , Martinez MA. Recycling of aluminium alloy and aluminium matrix composite chips by pressing and hot extrusion. Journal of Materials Processing Technology. 2003;143-144:792-5.

[9] Samuel M. A new technique for recycling aluminium scrap. Journal of Materials Processing Technology. 2003;135:117-24.

[10] Tekkaya AE, Schikorra M, Becker D, Biermann D, Hammer N, Pantke K. Hot profile extrusion of AA-6060 aluminum chips. Journal of Materials Processing Technology. 2009;209:3343-50.

[11] Gronostajski JZ, Kaczmar, J.W., Marciniak, H., Matuszak A. Production of composites from Al and AlMg2 alloy chips. Journal of Materials Processing Technology. 1998;77:37-41.

[12] Gronostajski J, Matuszak A. The recycling of metals by plastic deformation: an example of recycling of aluminium and its alloys chips. Journal of Materials Processing Technology. 1999;92-93:35-41.

[13] Gronostajski JZ, Marciniak, H., Matuszak, A., Samuel M. Aluminium-ferro-chromium composites produced by recycling of chips. Journal of Materials Processing Technology. 2001;119:251-6.

[14] Chmura W, Gronostajski J. Mechanical and tribological properties of aluminium-base composites produced by the recycling of chips. Journal of Materials Processing Technology. 2000;106:23-7.

[15] Gronostajski J, Chmura W, Gronostajski Z. Phases created during diffusion bonding of aluminium and aluminium bronze chips. Journal of Achievements in Materials and Manufacturing Engineering. 2006;19:32-7.

[16] Schikorra M, Pantke, K., Tekkaya, A.E. , Biermann D. Re-use of AA6060, AA6082, and AA7075 aluminum turning chips by hot extrusion. 9th International Conference on Technology of Plasticity, ICTP 2008: Hanrimwon Publishing Co., 206-3 Ojang-dong, Jung-gu, Seoul, 100-310, Korea, Republic of; 2008. p. 902-7.

[17] Mindivan H, Cimenoglu H, Kayali ES. Production of the composite from 6082 Al alloy chips and fly ash particles by hot pressing. TMS Annual Meeting2009. p. 71-5.

[18] Haase M, Ben Khalifa, N., Tekkaya, A. E., Misiolek, W. Z. . Improving mechanical properties of chip-based aluminum extrudates by integrated extrusion and equal channel angular pressing (iECAP). Materials Science and Engineering: A. 2012;539:194-204.

[19] Güley V, Güzel A, Jäger A, Ben Khalifa N, Tekkaya AE, Misiolek WZ. Effect of die design on the welding quality during solid state recycling of AA6060 chips by hot extrusion. Materials Science and Engineering: A. 2013;574:163-75.

[20] Misiolek WZ, Haase, M., Ben Khalifa, N., Tekkaya, A.E., Kleiner M. High quality extrudates from aluminum chips by new billet compaction and deformation routes. CIRP Annals - Manufacturing Technology. 2012;61:239-42.

[21] Suzuki K, Huang, Xin Sheng, Watazu, Akira, Shigematsu, Ichinori,, Saito N. Recycling of 6061 aluminum alloy cutting chips using hot extrusion and hot rolling. Materials Science Forum. 2007;544:443-6.

[22] Chiba R, Nakamura T, Kuroda M. Solid-state recycling of aluminium alloy swarf through cold profile extrusion and cold rolling. Journal of Materials Processing Technology. 2011;211:1878-87.

[23] Allwood J, Huang Y, Barlow C. Recycling scrap aluminium by cold-bonding. 8th International Conference on Technology of Plasticity. Verona2005.

[24] Cui J, Werenskiold JC, Roven HJ. New approaches for recycling of aluminum scraps. TMS Annual Meeting2009. p. 389-96.

[25] Cui J, Kvithyld A, Roven H. Degreasing of Aluminium Turnings and Implications for Solid-State Recycling. Minerals, Metals and Materials Society/AIME, 420 Commonwealth Dr., P. O. Box 430 Warrendale PA 15086 USA; 2010.

[26] Suzuki K, Shigematsu, Ichinori, Imai, Tsunemichi,, Saito N. Influences of chip characteristics and extrusion conditions on the properties of a 6061 aluminum alloy recycled from cutting chips. Japan Institute of Light Metals 2005;55:395-9.

[27] Hu M-L, Ji Z-s, Chen X-y. Effect of extrusion ratio on microstructure and mechanical properties of AZ91D magnesium alloy recycled from scraps by hot extrusion. Transactions of Nonferrous Metals Society of China. 2010;20:987-91.

[28] V. Güley, Khalifa NB, Tekkaya AE. The Effect of Extrusion Ratio and Material Flow on the Mechanical Properties of Aluminum Profiles Solid State Recycled from 6060 Aluminum Alloy Chips. The 14th International ESAFORM Conference on Material Forming: American Institute of Physics; 2011. p. 1609-14.