Formability of aluminium sheets manufactured by solid state recycling

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Abstract. Conventional recycling practices for non-ferrous metallic scrap involves melting followed by purification. This practice is suitable for recycling when the large volume of scrap is available. Though such recycling reduces consumption of diminishing metallic resources, high energy requirement and material loss during melting and purification limit its applicability. In the present work, manufacturing of solid state recycled aluminium sheet by hot rolling is explored and its formability characterized. Aluminium chips were divided into smaller particles (1~2mm) by crushing. After stress relief annealing, chips were cold compacted into square slabs (75*75mm section) of different thicknesses. Another similar set of slabs was made by hot compaction. The compacted slabs were hot rolled over a number of passes at 400°C. Each slab was reduced to approximately 90% thickness to get the sheet thickness in the range of 0.6 to 1.5 mm. Microstructure revealed good interface bonding between the chip particles. Mechanical properties of the sheet from room temperature up to 200°C and at different strain rates were characterized by a number of tensile tests. Circular blanks from sheet were drawn into cylindrical cups and strain distribution was observed along different directions of rolling using circle grid analysis.

1. Introduction

Non-ferrous metals, mainly aluminium and it’s alloys are widely used in automotive and aerospace industries because of its light weight and high strength to weight ratio. During machining of their semi-finished products, a large amount of scrap in the form of chips and discards is generated. This scrap is generally returned to melting, where some amount of metal is recovered and again utilized in the production process. It is called as conventional recycling process. The metal yield rate in the conventional recycling of aluminium scrap is very less that is only 55% [1].

To avoid this problem of using conventional recycling process, an alternate process of recycling is developed called as solid state recycling. In this process, metal scrap is directly converted into finished products without melting. In the case of direct conversion using solid state recycling, the loss is the part of chips from which impurities cannot be removed (2%) and hot plastic working losses up to 3% [1]. Therefore metal yield rate is around 95%.
There are two types of scrap - end of life scrap and production scrap. Production scrap is regularly available, is more pure than the ore and is, therefore, viable material for the direct manufacture of products without melting.

Gronostajski et al. [2] described a method for solid state recycling of aluminium alloy swarf into bar-shaped products through granulating, pre-pressing and hot extrusion. Fogagnolo et al. [3] studied a method for recycling of aluminium alloy swarf by cold/hot pressing followed by hot extrusion. A method of aluminium chips recycling by hot extrusion and hot rolling is proposed by Suzuki et al. [4]. Chiba et al. [5] investigated the possibility of solid-state recycling of aluminium alloy machining swarf using cold profile extrusion and cold rolling process. Haase et al. [6] investigated direct conversion of aluminium alloy AA6061 chips into finished products by hot extrusion followed by cold extrusion. So far, all researchers have worked on solid state recycling using extrusion followed by subsequent plastic deformation processes.

In the present work, a new method of solid state recycling using compaction followed by hot rolling was developed. In this method, prepared aluminium chips were cold and hot compacted into square slabs. These slabs were further hot rolled into metallic sheets. Sheets were characterized for microstructure and mechanical properties at room temperature and high temperature. In addition, cylindrical cups were drawn from sheet blanks and formability of sheets manufactured using solid state recycling is discussed.

2. Experimental procedure

2.1. Material
In this experiment, commercially available aluminium 6000 series alloy (Al 6082) chips were used as raw material. The composition of this alloy is shown in table 1. Figure 1 shows the scanning electron microscopy (SEM) image of Al 6082 alloy chip particle.

| Table 1. Chemical composition of aluminium alloy Al 6082 (wt%). |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Mg              | Si              | Cu              | Ti              | Al              |
| 1.63            | 0.83            | 0.42            | 0.16            | Bal.            |

Figure 1. SEM image of chip particle surface.

2.2. Chip preparation
Al 6082 alloy chips were collected from the machine shop. Chips were pulverized by hammering and crushing using sigma blade mixer. Particles of size less than or equal to 5mm were separated out by sieving for further processing into rolled sheet. The prepared chip particles are shown in figure 2 (a). These particles were cleaned using an aqueous solution of soap followed by ultrasonic acetone bath. Chip particles were annealed at the temperature of 400°C for 1 hour. After annealing of chips, fragmented grains were converted into new grains as shown in figure 2 (b) and (c).
2.3. Compaction of chips
Prepared chip particles were cold compacted at room temperature and hot compacted at 300°C into square slabs of dimension 75*75mm. The thickness of cold compacted slabs varies from 8.2mm to 9.55mm and of hot compacted slabs varies from 9.4mm to 10.6mm. All the compactions were carried out using the hydraulic press of capacity 2000kN.

![Figure 2. (a) Prepared chip particles (b) grain structure of as received chips and (c) annealed chips.](image)

2.4. Rolling of compacted slabs
Two types of processes were used to prepare aluminium alloy sheets. One process is cold compaction followed by hot rolling and another one is hot compaction followed by hot rolling. Compacted slabs were hot rolled at 400°C into sheets of different thicknesses using a rolling machine of capacity 700kN. Slabs were heated up to 450°C to compensate for the heat loss while transferring from the furnace to the rolling machine. Roll speed was maintained at 2826mm/sec and it was kept constant for all slabs. Roll gap of 0.5mm to 8mm was maintained depending on the initial thickness of the slab. Slabs were rolled twice. During first rolling, the thickness of slabs was reduced by 60 to 70% of initial thickness using 5 to 6 roll passes. After first rolling, slabs were annealed and solution heat treated.

![Figure 3. Hot rolled sheets.](image)

After first rolling, sheets were annealed at 400°C for diffusion to taking place among chip particles. After annealing, they were solution treated because solution treated condition is suited to plastic deformation. Solution treatment was carried out at 540 °C for 1 hour followed by water quenching at room temperature. Sheets were rolled second time to achieve final thickness after solution treatment. The formed sheets after second rolling underwent two heat treatments. One was annealing at 400 °C and second was the T6 heat treatment. In T6 heat treatment, sheets were solution treated at 540 °C for 1 hour followed by water quenching and artificially ageing at 180 °C for 24 hours.
2.6. Microstructure
The microstructural investigation was performed using an optical microscopy to study bonding between chip particles and structural homogeneity. The specimens for optical microscopy were polished and etched with Keller's etchant.

2.7. Tensile testing
Room temperature uniaxial tensile testing was performed at a strain rate of 0.001/sec using Tinius Olsen UTM of capacity 50kN. The gauge length and width of cold tensile samples was 15mm and 4mm, respectively and they were in annealed and T6 heat treated condition. Hot uniaxial tensile testing was performed at different combination of temperatures (100°C, 150°C and 200°C) and strain rates (0.01/sec and 0.001/sec) using a Gleeble-3800 thermo-mechanical simulator. E type thermocouple was spot welded at the center of the gauge length to monitor the sample temperature. The gauge length and width of hot tensile samples was 10mm and 6.35mm, respectively and they were in T6 heat treated condition. The thickness of both the type of tensile specimens was varying from 0.7mm to 1.5mm. The strain was measured using ratio of change in gauge length to original gauge length. Change in gauge length was given by tensile testing machine. The samples for cold tensile testing and hot tensile testing were shown in figure 4 (a) and (b) respectively. The room temperature tensile test was conducted to evaluate mechanical properties such as ultimate tensile strength (UTS), yield strength (YS) and % elongation. Whereas, hot tensile test was conducted to investigate hot temperature behavior of sheets at various strain rates. Tensile tests were replicated 3 times.

Figure 4. (a) Cold tensile samples (b) Hot tensile samples.

2.8. Cup drawing of sheet
Circular blanks of diameter 50mm were cut from rolled sheets. The initial thickness of the blanks for cup drawing test was varying from 0.7mm to 1.5mm and all the blanks were in annealed condition. Circular grid pattern was laser marked with depth of impression 0.03mm on one side of blanks as shown in figure 5. The initial diameter of grid circles was 2mm and center to center distance between grid circles was 2.5mm. The cylindrical cups were drawn from circular blanks with a draw ratio 2. The punch radius was 5mm. The test parameters were maintained as BHF = 8kN, speed = 8.5mm/sec and grease was used for lubrication. In plane, major strain and minor strain measurements were carried out using a Camscope. Thickness strain was calculated by volume constancy.

Figure 5. Circular blank with laser marked circular grid pattern.
3. Results and discussion

3.1. Microstructure investigation
Optical micrographs of rolled sheet before annealing and after annealing were shown in figure 6. It is observed that uniform grains are formed after annealing. Diffusion bonding takes place between chip particles. Due to diffusion, grain boundary formation takes place between chip-particle interface. Also, there is no porosity present after annealing and sheet become a solid sheet metal.

![Optical micrographs of rolled sheet](image)

Figure 6. Optical micrographs of rolled sheet (a) after annealing (b) before annealing.

3.2. Mechanical properties
The stress-strain curves obtained from room temperature tensile testing of cold compacted-hot rolled and hot compacted-hot rolled sheets along the rolling and perpendicular to rolling direction after annealing are shown in figure 7(a). The stress-strain curves for cold compacted-hot rolled and hot compacted-hot rolled sheets after T6 heat treatment are shown in figure 7(b).

In T6 heat treated condition, hot compacted sheets shows higher modulus of elasticity as compared to cold compacted sheets by 2.2 GPa. During hot compaction, voids present between particles of chip significantly reduce and more densification takes place as compared to cold compacted slabs. During further deformation by rolling, the maximum amount of energy is utilized for plastic deformation. Therefore, the particles significantly get diffused in hot compacted sheets as observed from micrographs(figure 6(a)). Because of this, hot compacted sheet shows higher modulus of elasticity.

Even though it is seen from the figure 7(b), there is significant difference in modulus of elasticity according to rolling orientation, numerically it is negligible.

In annealed heat treated condition, the UTS, YS and % elongation are achieved up to 147MPa, 92MPa and 24% respectively (figure 7(a)). After T6 heat treated condition, the UTS increased up to twice and % elongation is reduced to half of that in the annealed condition. The UTS, YS and % elongation after T6 condition are achieved up to 280MPa, 157MPa and 12% respectively (figure 7(b)). It is observed that the strength and % elongation of cold compacted-hot rolled sheets is greater than that of hot compacted-hot rolled sheets in both the heat treated conditions.

The uniaxially deformed tensile samples after room temperature tensile testing are shown in figure 8. It can be observed from the samples that the uniaxial deformation behavior of cold compacted-hot rolled sheets shows ductile failure.
Figure 7. The stress-strain curves of sheets (a) after annealing and (b) after T6 heat treatment.

The variation in % elongation, UTS and YS of sheets with temperature at strain rates of 0.001/sec and 0.01/sec are shown in figure 9. It is observed that the UTS and YS decreases with increase in temperature (figure 9 (a) and (b)). The UTS, YS and % elongation increase with an increase in the strain rate. The increase in YS with increase in strain rate is more significant at low temperature.

Figure 8. uniaxially deformed tensile samples after room temperature tensile testing.

Figure 9. (a) Variation in % elongation and UTS with temperature (b) Variation in YS with temperature.
3.3. Strain distribution in drawn cylindrical cups

The cylindrical cups drawn from gridded circular blanks and the deformed circles after drawing are shown in figure 10(a) and (b) respectively. It is observed that cups of 20mm height could be easily drawn with good wall strength and without necking.

The thickness strain distribution along three different directions (0°, 45° and 90°) to rolling, for cylindrical cups drawn from (a) cold compacted-hot rolled and (b) hot compacted-hot rolled sheets is shown in figure 11 (a) and (b) respectively. The maximum thickness strain achieved for cup drawn from cold compacted-hot rolled sheet is -0.53 and for cup drawn from hot compacted-hot rolled sheet is -0.50. Maximum thickness strain occurred at the bottom corner radius of the cup in both the sheets. However, the thickness strain variation is independent on rolling direction of the sheet. Strain hardening exponent of cold compacted-hot rolled sheet is 0.29 and of hot compacted-hot rolled sheet is 0.22. Cold compacted-hot rolled sheet is capable of greater thinning without necking due to its high strain hardening exponent.

![Figure 10. (a) Drawn cylindrical cups (b) Deformed circle grid pattern.](image)

![Figure 11. Thickness strain distribution along outer surface of cup; (a) drawn from cold compacted-hot rolled sheet and (b) drawn from hot compacted-hot rolled sheet.](image)

The major and minor strain distribution along three different directions (0°, 45° and 90°) to rolling for cylindrical cups drawn from cold compacted-hot rolled and hot compacted-hot rolled sheets is shown in figure 12 (a) and (b) respectively. Both, cold compacted-hot rolled and hot compacted-hot rolled sheets gives three modes of deformation as uniaxial mode, biaxial mode and plain strain mode. It is observed that major strain and minor strain variation is also independent on rolling direction of sheet.
Figure 12. Major and minor strain distribution along outer surface of cup; (a) drawn from cold compacted-hot rolled sheet and (b) drawn from hot compacted-hot rolled sheet.

4. Conclusions
Solid state recycling of aluminium machining scrap by rolling it into thin sheets has been demonstrated. Strain distribution along different directions with respect to that of rolling, in cylindrical cups, was observed. Following conclusions emerged from the study.

- Annealing heat treatment helps in softening as well as diffusion bonding among particles of chip.
- Cold compacted-hot rolled sheets shows better properties in annealed condition (UTS = 146.7MPa, % elongation = 24.2%) as well as in T6 heat treated condition (UTS = 279.31MPa, % elongation = 12.06%).
- Due to high % elongation in annealed condition, cold compacted-hot rolled sheets can be deep drawn into cups after annealing. The strength of cup can be increased by performing T6 heat treatment after drawing.
- Increase in YS with increase in strain rate is more significant at low temperature.
- Strain hardening exponent of cold compacted-hot rolled sheet (n = 0.29) is greater than hot compacted-hot rolled sheet (n=0.22) which helps in more thinning without failure.
- Cups drawn from both cold compacted-hot rolled and hot compacted-hot rolled sheets gives three major, discernible modes of deformation, namely, uniaxial mode, biaxial mode and plain strain mode.

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