Effect of reduction ratio in flow forming process on microstructure and mechanical properties of a 6082 Al alloy

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Abstract. Flow forming is a cold deformation process in which hollow cylindrical or conical parts with different geometric configurations are produced using tools such as balls, rollers, or flow forming wheels on specialized mandrels. Because it enables the production of parts without any further modifications or with minimal modifications before their use in service, the process is categorized as an NSF technology (net-shape forming), and therefore the flow formed parts can be considered as a final product. The aim of this study is to investigate the microstructure and mechanical properties of a flow formed 6082 Al alloy, which was initially in W-temper condition. Hollow cylindrical preforms were first manufactured by machining, and subsequently solution heat treated and quenched. Then, the parts were flow formed with 3 different reduction ratios (45%, 55% and 65%) prior to aging at 177 °C for 8 h to achieve T8 temper condition. Microstructures of the flow formed parts were examined by an optical microscope, and hardness and tensile tests were conducted. The results revealed that increasing reduction ratio slightly decreases hardness and strength with almost constant ductility.

Introduction

Al-Mg-Si alloys (6xxx series alloys) are commonly used heat treatable Al alloys because they offer a combination of high strength, high corrosion resistance, good weldability and low density. In order to obtain appropriate mechanical strength, 6xxx Al alloys are frequently extruded, shaped, and then artificially aged. During these forming processes, the material is subjected to different levels of stress and deformation, precipitation of the second phases occurs in the microstructure of the deformed material during subsequent aging, and the pre-deformation history significantly affects the precipitation behavior and the aging response [1]. Cold working after solution heat treatment and quenching causes nucleation sites for finer precipitates, which further increases strength [2].

The flow forming is a metal forming method which is used to produce hollow cylindrical parts or conical elements by using tools in the form of balls, rollers, or flow forming wheels on a particular mandrel. In order to extrude the material under pressure in the axial direction, the material must first be brought to the state of plastic flow. As a result, the workpiece's length increases and its diameter decreases [3]. During flow forming, the amount of applied plastic deformation is controlled by various process parameters. The most important parameter among them is reduction ratio, namely, percent deformation through the thickness direction.

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Most of the studies concerning flow forming processes include surface roughness prediction depending on the flow forming parameters [4], residual stress estimation [5], forming forces arising from the process variables, and investigation the relationships between the microstructure and the mechanical properties of flow formed materials. In this context, De et al [4] investigated the surface roughness of an H30 aluminum alloy after being flow formed, and established a correlation between the surface roughness and the flow forming parameters. Srivastwa et al [6] measured the flow forming forces depending on the feed rate and the rotational speed of the mandrel during flow forming process of 2014 and 7075 Al alloys in annealed condition. They found that effect of varying feed rate had a higher effect on the resulting forming forces than the effect of the varying rotational speed. They also reported that axial force was the dominant force with respect to radial and circumferential forces. Haghshenas et al [7] investigated the mechanical properties 5052 and 6061 Al alloys after 20 to 60% flow forming. They reported that the yield strength of both alloys increased after the flow forming, with the increment in 5052 Al alloy was 47% higher than that of 6061 alloy due to a higher strain hardening coefficient of 5052 Al alloy. Gao et al [8] investigated the effect of recrystallization and solution annealing heat treatments on the microstructures and mechanical properties of a flow formed 2219 Al alloy. They reported that the flow forming increased strength and decreased ductility. Following the recrystallization annealing at 435°C for 30 min, strength of the flow formed samples decreased first, and increased again with increased recrystallization temperature. For the solution annealing heat treatment conducted after the flow forming, both strength and ductility increased with increasing solution annealing temperature. As seen from the previous works, aluminum alloys were subjected to flow forming process to investigate their response to flow forming in the view point of their surface quality and the final mechanical properties after being flow formed. It is therefore, the main aim of the present work is to investigate the effect of reduction ratio during flow forming process, and subsequent aging on the microstructure and mechanical properties of a 6082 Al alloy.

Experimental Procedure

6082 Al preform tubes were first solution annealed (W-temper condition) at 530 °C for 1 h, and then quenched in 20 vol.% polymer containing water [9]. The flow forming process was performed on solution treated alloy in W-temper condition in three different reduction ratios (45%, 55% and 65%), and finally the tubes were aged at 177°C for 8 h. Fig. 1 shows an image of preform material (left) and flow-formed materials (with increasing reduction ratio from left to right). The preform and the flow formed tubes were hereafter designated as Preform, S45, S55 and S65 samples according to the reduction ratio.

Fig. 1. General view of the preform (left) and flow formed 6082 Al tubes with increasing reduction ratios of 45%, 55%, and 65% from left to right.

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Microstructures of the preform and the flow formed samples were examined under an Olympus BX53M optical microscope after being prepared by standard metallographic procedure [10] and etched by 25 s immersion into the Groesbeck's reagent (100 ml water, 4 g NaOH, 4 g KMnO4). Hardness of the samples was measured by an Emco Test DuraScan 20 tester using a Vickers pyramid indenter and 300 g load according to ASTM E384 standard [11]. The hardness measurement was carried out through the thickness of the samples at regular intervals from the outer surface (in contact with the rollers) to the inner surface (in contact with the mandrel). The tensile tests were conducted on an Instron 3382 model universal testing machine using the samples, which were prepared according to ASTM E8/E8M standard [12] in the longitudinal direction to the forming direction.

Results and Discussions

Fig. 2 shows optical micrographs of the flow formed samples. As seen in Fig. 2a, the grains are clearly visible in S45 sample, as being approximately 20 μm length and 5 μm width grains, which were elongated along the flow direction. In the microstructures of S55 and S65 samples (Fig. 2b and c), the reduction ratio was higher, and the grains were not clearly visible due to higher amount of reduction on those samples. Despite all samples were subjected to aging heat treatment at 177°C for 8 h, there was no recrystallization in the microstructures due to a lower temperature of aging, which is insufficient for recrystallization. Considering the fact that recrystallization takes place easier when the reduction rate increases [13], it was seen that even 65% of reduction in the thickness direction did not lead to recrystallization of the samples.

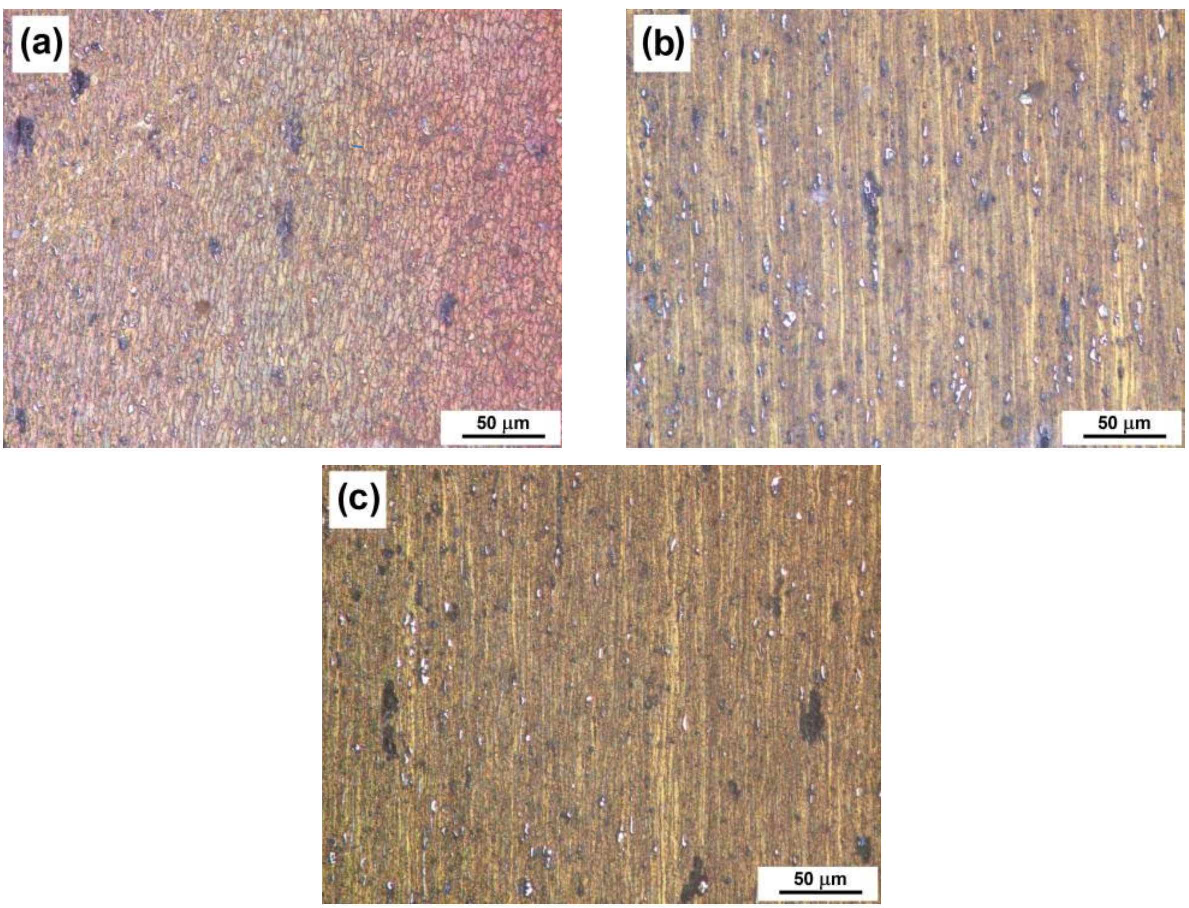

Fig. 2. Optical micrographs of the flow formed samples (a) S45, (b) S55, and (c) S65.

Table 1 lists the hardness of the flow formed samples. It is interesting to note that hardness of the flow formed and the aged samples slightly reduced when the reduction ratio increased. On the other hand, even though hardness of S45 sample close to the inner surface was slightly higher, there was no clear correlation between the hardness values depending on the hardness measurement locations.

Table 1. Hardness measurements of the flow formed and aged samples.

Hardness measurement locations	Hardness, HV0.3		
	S45	S55	S65
1 (close to outer surface)	99	92	93
2	103	96	96
3	98	93	99
4	101	92	93
5 (close to inner surface)	110	93	95

Tensile test results are listed in Table 2, and the stress – strain graphs are presented in Fig. 3. Similar to the hardness variation, strength values of S45 sample are slightly higher than those of S55 and S65 samples. However, the ductility, in terms of elongation, almost remained constant when the reduction ratio increases. Considering that lower reduction ratio results in a higher hardness and strength, and lack of hardness increment with increased reduction ratio, it was concluded that that age hardening mechanism is more effective than strain hardening mechanism in determining the final mechanical properties.

Table 2. Tensile test results of the flow formed and aged samples.

Properties	S45	S55	S65
Yield strength, [MPa]	272	262	268
Ultimate tensile strength, [MPa]	290	275	282
Elongation at fracture, [%]	11.8	11.3	10.8

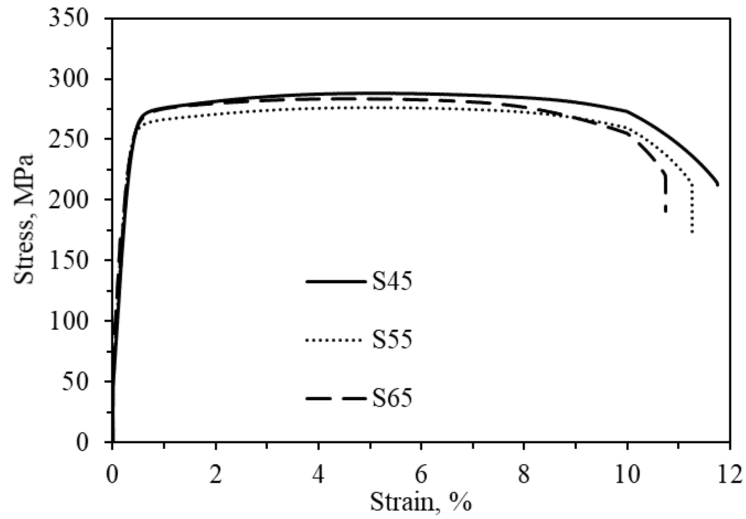

Fig. 3. Stress strain graphs of the flow formed and aged samples.

Summary

The effect of cold deformation by the flow forming on microstructure and mechanical properties of a 6082 Al alloy after the aging was investigated. As the reduction ratio increases from 45% to 65%, the grains are elongated along the flow direction. For lower reduction ratio (S45 sample), the grains are still visible, while, the grains were almost invisible in the samples subjected to reduction ratio (S55 and S65 samples). There was no recrystallization in the microstructures indicating the aging temperature (177°C) after the flow forming is insufficient for recrystallization to take place. Hardness and strength are the highest for the samples subjected to a lower reduction ratio during the flow forming. Increasing deformation slightly reduced hardness and strength, with exhibiting almost constant ductility. The obtained results finally indicate that age hardening mechanism in the present 6082 Al alloy is more effective in determining the final mechanical properties.

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