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Temperature and Die Angular Effect on Tensile Strength, Hardness, Extrusion Load and Flow Stress in Aluminum 6063 Processed by Equal Channel Angular Extrusion Method

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ABSTRACT

Developing aluminum with good mechanical properties like hardness, tensile strength, and normal flow stress, Equal Channel Angular Extrusion (ECAE) method has been suggested as a suitable metal forming process. The load applied and extrusion temperature normally influences the flow stress behavior in extruded products and determine their mechanical properties. Consequently, how these factors affect mechanical behavior and flow stress of Al 6063 processed by ECAE was examined in this study. Extrusion temperatures were 350°C, 425°C, and 500°C with die angles of 130°, 140°, and 150°. 5 mm/s of ram speed was applied. Each extrudate's tensile strength and hardness were measured using a Universal Testing Machine and a Rockwell hardness tester. Samples with equal dimensions and properties were also modeled using the Qform software at the extended die angle and temperature for proper analysis of flow stress in the extrudates. According to experimental results, the temperature had a greater effect on the tensile strength and hardness of the billet than the die angle. The extrudates' grains also became finer as the billet temperature rose. Simulation findings showed that higher billet temperature led to a decrease in the extrudates' flow stress. The simulation also demonstrated that billet temperature had a greater impact on extrusion load than die angle, with a maximum extrusion load of 5.5 MN being attained at 350 °C.

Keywords: die angle, simulation, aluminum, temperature, tensile strength

INTRODUCTION

Aluminum has become one of the popular raw materials for engineering applications due to its distinctive qualities, which include good ductility, corrosion resistance, lightweight, thermal conductivity, and other features [1]. Its wider application in manufacturing, home appliance, maritime, aviation, and construction industries can be attributed to these properties. Unfortunately, aluminum products have poor fatigue strength, inadequate hardness, and flow stress within the components [2]. Numerous improvements have been made to the metallurgical and mechanical properties of aluminum products. Extrusion is one of these methods, which entails using a punch to push heated metal through a die with the aid of load application from the hydraulic press [3]. To extrude metal into a variety of shapes, plastic deformation is required [4]. Extruded materials undergo substantial changes in terms of mechanical and metallurgical properties as a result of this process [5].

Equal Channel Angular Extrusion (ECAE), among all extrusion techniques has been proven to be effective [6]. Due to severe plastic deformation, ECAE enables the production of fine-grain structures in a single pass [7]. During the ECAE process, two die channels have equal cross-sectional areas and intersect at an angle that is typically between 90° and 150° [6]. When a material sample, usually referred to as a billet, is pushed through the die's channel angle under high pressure, deformation occurs [8]. Materials of Equal cross-sectional area flow out of the die after the extrusion process when compared to the sample before extrusion [9]. This can be very helpful in numerous industrial applications where bulk materials require refined grain texture and structure [10].

According to several reports, ECAE's ultrafine grain materials can maintain both high strength and ductility. Mohammed and Senthil [11], reported that metals can exhibit a special blend of strength and ductility when their grain is refined through severe plastic deformation. In the creation of innovative structural components for future generations, such excellent mechanical properties are highly desired. However, further processing is required to obtain a microstructure that increases the material's ductility [12].

ECAE products are characterized by expensive manufacturing processes [13] which has affected its production rate. There are also reported cases of inadequate flow stress in extruded products, which causes low production quality [14]. Die angle and billet temperature inadequacies may be the cause of these challenges [14]. The material under consideration could get damaged, take additional processing time, and result in higher manufacturing costs if either the die angle or the billet temperature is higher than necessary [15]. The products' quality, including their hardness, however, is diminished by inadequate die angles or temperatures [16]. To have an excellent route of quality aluminum 6063 production, it is necessary to look at the flow stress, tensile strength, and hardness of aluminum 6063 extruded at different temperatures and die angles. This study employed both experimental and modeling techniques.

EXPERIMENTAL PROCEDURE

The Queentech Aluminum Company was responsible for the supply of aluminum 6063 samples, which were then cut into a billet ($12\times12\times42$ mm^3) (Figure 1a). The billets were processed using a milling machine to produce a smooth surface finish (Figure 1b). Glow Discharge Mass Spectrometer (BEL 2480) was used to examine the parent material's chemical composition. The dimension of the billet was selected to enable enough clearance against the $12.1\times12.1\times58$ mm^3 (square cross-section) ECAE die (Figure 2a). The samples were cleaned before being subjected to heating at the desired temperatures of 350°C, 425°C, and 500°C in an electric furnace. Each heated billet specimen was put into the lubricated ECAE die at a varied angle (130, 140, and 150°). The ECAE die was paired with the punch (Figure 2b), which was used to drive the billet out of the die. A steady 6 MN load was applied to the hydraulic press (BMT 520) while the billet, punch, and die were assembled (Figure 2c). The full schematic diagram of ECAE is presented in Figure 2d. Nine experimental runs were conducted and the ram speed was held constant at 5 mm/s.

Test for tensile strength and hardness

Samples were machined following ASTM B321M standards and put through a tensile test on the Universal Testing Machine (UTM). Rockwell hardness testing equipment was used to measure the samples' hardness after grinding and polishing to obtain a smooth surface finish. These smoothened samples were set up on a device for measuring Rockwell hardness, from which the hardness values were obtained. Three measurements of the aluminum 6063 extrudates' tensile strengths and hardness were taken, and the average results were computed and examined

ECAE process simulation

The Qform program, a commercial finite element-based program for simulation, optimization, and analysis of aluminum forming procedures was used to simulate the ECAE process. The simulation and analysis of the stress flow in the extruded samples at different die angles and temperatures were investigated. There are three stages to the simulation process: preparation, processing, and postprocessing [17]. Preprocessing involved constructing configurations equivalent to those used in the experiments while imposing only a few assumptions, like isotropic, homogeneous, and visco-plastic deformation. The workpiece and the

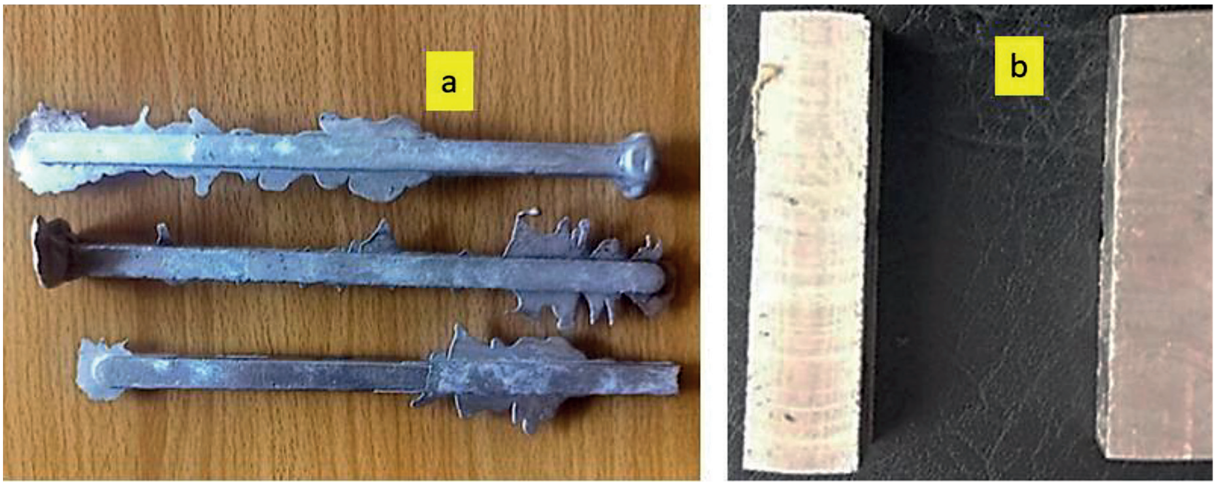

Figure 1. Samples of aluminum (a) before, and (b) after milling

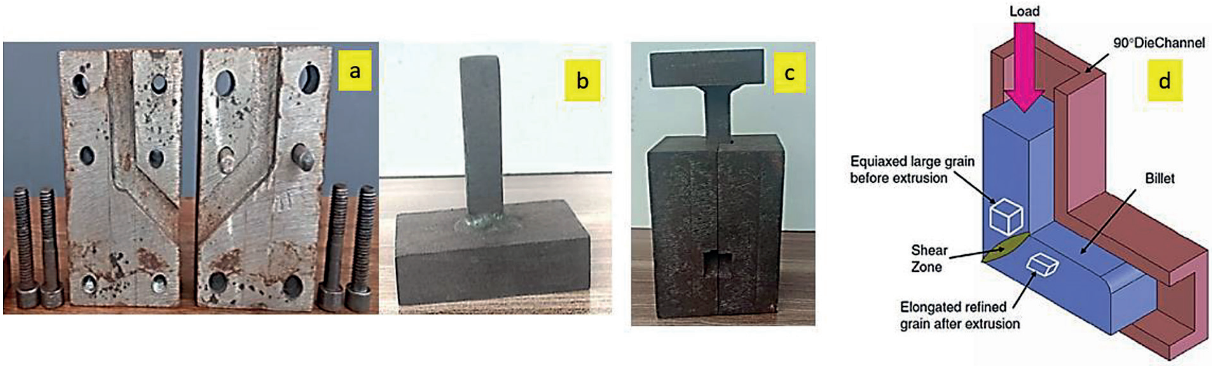

Figure 2. ECAE component (a) die with angle, (b) punch, (c) die and punch assembly, (d) schematic diagram of ECAE process

die experienced very little friction because of the lubrication, and the press machine supplied compressive load at 5 mm/s extrusion speed. Air was used as the cooling medium while the plane strain factor was considered

The typical extrusion material flow formulation in the Qform platform, according to Nickolay et al [18], consists of the dynamic, constitutive, compatibility, incompressible energy balance, and flow stress equations presented in equations (1-6) respectively.

$$\sigma_{ij,j} = 0 \tag{1}$$

$$\sigma_{ij} = \frac{2}{3}\frac{\bar{\sigma}}{\dot{\bar{\varepsilon}}}\,\varepsilon_{i,j} \tag{2}$$

$$\varepsilon_{ij} = \frac{1}{2}\left(V_{i,j} + V_{j,i}\right) \tag{3}$$

$$V_{i,i} = 0 \tag{4}$$

$$\rho c T = (k\,T_i), i + \beta\,\bar{\sigma}\,\dot{\bar{\varepsilon}} \tag{5}$$

$$\bar{\sigma} = \bar{\sigma}\,(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \tag{6}$$

where: $\varepsilon_{ij}, \sigma_{ij}, V_{i,j}$ – respectively strain rate, stress, and velocity components.

$\bar{\varepsilon}, \dot{\bar{\varepsilon}}, \bar{\sigma}$ – respectively effective strain, effective strain rate, and effective stress.

ρ, k, c – respectively density, thermal conductivity, and specific heat.

β, T – respectively the heat generation efficiency and temperature.

All the simulation's input parameters came from an earlier ECAE experiment that was carried out. The simulation considered a load of 6 MN with die angles of 150, 140, and 130° at 500, 425, and 350 °C as presented in Table 2.

RESULTS

Elemental composition, tensile strength, and hardness result

The elemental makeup of the unprocessed aluminum 6063 sample is displayed in Table 1. The response agrees with the typical aluminum 6063 sample, in which Mg dominates at a concentration of 0.6%. The results of the extruded samples' tensile strength and hardness at various die angles and temperatures are displayed in Table 2. Tensile strengths are 252, 248, and 253 MP for die angles of 130, 140, and 150°, respectively, at a constant temperature of 350 °C. This gives a maximum deviation of 5 MPa and ditto for other temperatures. Nevertheless, when the die angle was maintained at 130°, the tensile strengths were 305, 300 and 252 MPa for extrusion carried out at 500 °C, 425 °C, and 350 °C, respectively, indicating the largest gap of 53 MPa. Likewise, at the three levels of temperature, tensile strengths of 248, 288, and 304 MPa are produced for a die angle of 140°, and 253, 297, and 305 MPa for a die angle of 150°. This implies that the mechanical properties of the extrudate rely more on extrusion temperature than the die angle. Figure 3 makes it simpler to observe this variance. It is clear how extrusion temperature is more relevant than die angle in determining the hardness and tensile strength of aluminum products.

The hardness values of the extruded samples range from 94 to 112 HRB while the hardness of the parent materials is 84 HRB. Hardness and tensile strength results follow the same pattern. The hardness values for 130, 140, and 150° die angles are 94, 96, and 95 HRB, respectively, suggesting the reduced impact of the die angle at a constant temperature of 350 °C. The temperature has a substantial impact because the hardness values at 130° die angle are 94, 104, and 112 HRB, respectively, at extrusion temperatures of 350, 425, and 500 °C [19]. The increased effect of extrusion temperature on the die angle may be caused by recrystallization and grain development at higher temperatures [20]. The enhanced properties are due to the grain structure refinement at this temperature, which results in ultrafine grains with multiple grain boundaries that naturally resist dislocation movement during deformation [21].

Simulation result for the temperature effects on the Flow Stress

Figure 4a-c depicts the extruded billets' stress flow at specified temperatures of 500, 425, and 350 °C with a die angle of 120°. The stress level declined as temperature increased, indicating that high temperature reduces stress in the stress flow. Winholtz [22] asserts that a decrease in metal yield strength results from greater thermal stress induced by high temperatures. Metal experiences microscopic plastic deformation at this temperature, therefore, releasing parts of flow stresses.

The plastic deformation of the billet generates the flow stress at 350 °C [23]. The flow stress dominates within the range of 254.4 and 176.5 MPa (Figure 4a). The minimum and maximum stress values decreased to 110.8 and 183.3 MPa, respectively, at a greater temperature of 425 °C (Fig. 4b). Similar results were obtained at 500 °C extrusion temperature, where the minimum and maximum flow stress values dropped further to 60.28 and 109.4 MPa, respectively (Figure 4c). Figure 5a demonstrates

Table 1. Result of aluminum 6063's chemical composition

Element	Fe	Si	Cu	Mg	Mn	Zn	Cr	Sr	Ti
Composition (%)	0.17	0.44	0.004	0.6	0.01	0.001	0.002	0.05	0.01

Table 2. Hardness and tensile strength as an output variable to temperature and die angle

S/N	Input variables		Output variables	
	Die angle (°)	Temp (°C)	TS (MPa)	Hardness (HRB)
	Control sample		245	84
1	130	350	252	94
2	140	350	248	96
3	150	350	253	95
4	130	425	300	104
5	140	425	288	98
6	150	425	297	102
7	130	500	305	112
8	140	500	304	110
9	150	500	305	112

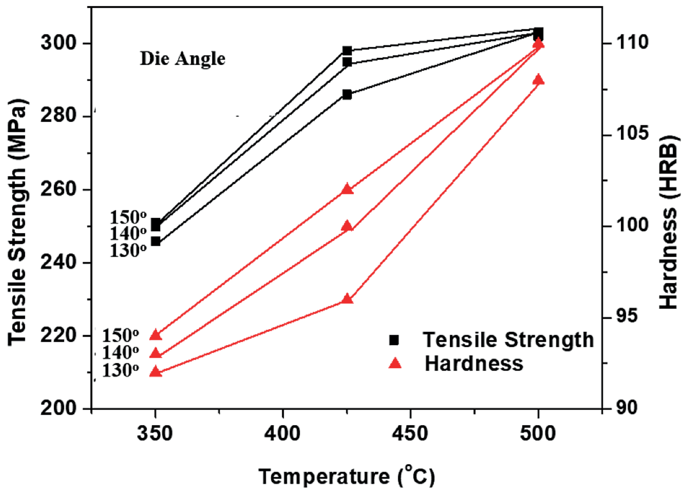

Figure 3. Variations in tensile strength and hardness due to variations in extrusion temperature at die angles of 130, 140, and 150°

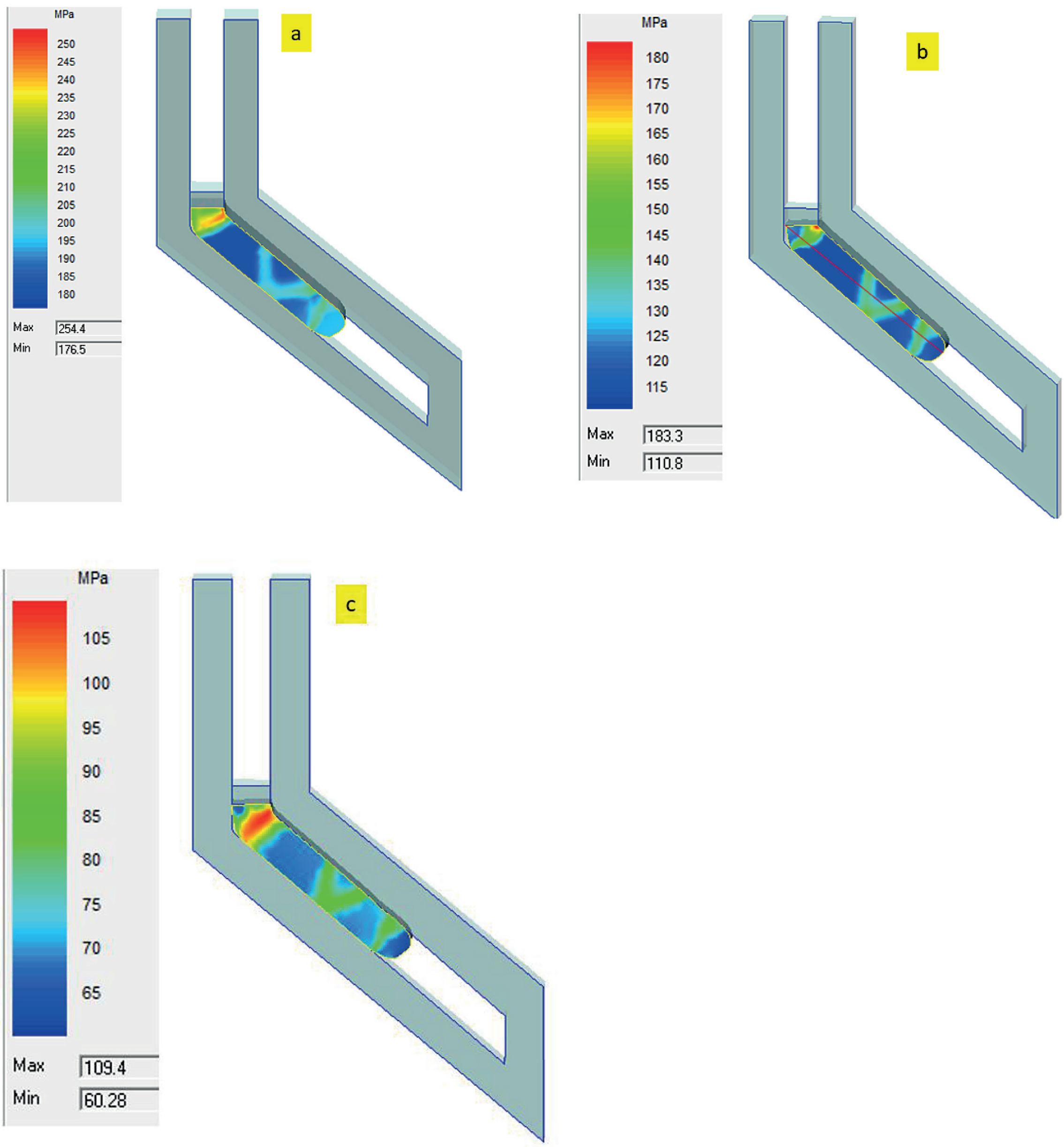

Figure 4. Extruded specimen's flow stress under temperature: (a) 350 °C, (b) 425 °C, (c) 500 °C

the observed reduction in flow stress as extrusion temperature approaches the melting point of aluminum [21]. The figure further highlights the significant role that temperature plays in the ECAE process, particularly in aluminum alloys [24]. As seen in Figure 4, it appears that the flow stress in all samples is not uniform with respect to variations in extrusion temperature. To rectify this, the samples can go through numerous extrusion passes to produce aluminum with minimal stress gradients. Such a smaller stress gradient is a quality indicator of high-strength aluminum [25].

The load versus distance for billets extruded at various temperatures is shown in Figure 5b. There are three main stages to the deformation behavior [26]. The first stage involves a quick increase in extrusion load which is an indication that the billet is forced downward toward the corner of the die. The second stage is the load declination as the billet reaches the angular portion of the die. The dwelling of the extrusion load, which refers to the stable state of the operation when billets are continuously flowing through the corner of the die, comes next as the third stage. This signifies the maximum load at which extrusion occurs. The load finally dropped to zero and indicating that the deformation cycle is completed. The maximum extrusion load of 5.5 MN is required at a temperature of 350 °C, as noticed, and reduces as the extrusion temperature rises [18]. It substantially decreases to 4.8 MN and 4.5 MN, respectively, at 425 °C and 500 °C. The flow stress falls with high temperature thus, processing time decreases [27-28] and this can be used as the justification for the considerable reduction in load.

Impact of angularity on the flow stress

Using a die angle less than 130° indicated no influence on the extrusion load of the ECAE process, according to the simulation done so far, but it has a visible impact on flow stress. This is evidenced in Figure 6a, b, which shows that the flow stress for extrusion performed at 150° and 110° varies by just 12.3 MPa, with larger stress observed at 110° die angle. However, the flow stress seems to be more uniform at a 150° die angle compared to 110°. This is most likely due to the decreased deformation rate resulting in decreased strain gradient [29]. Figure 6c-d further demonstrates that at a constant temperature, the extrusion loads are equal despite the variation in the die angle. Die angles 140 and 150° have equal 5.5 MN extrusion load at 350 °C. Using similar die angles, the samples were extruded at a load and temperature of 4.8 MN and 500 °C respectively. Theoretically, 5.4 MN is the maximum extrusion load required for an aluminum billet treated at 350 °C to extrude [30] which is also in agreement with the simulation results. The extrusion load, which mostly dictates the energy consumption in metalworking operations, is unaffected by larger die angles, but, it may shorten the extrusion time [31-32].

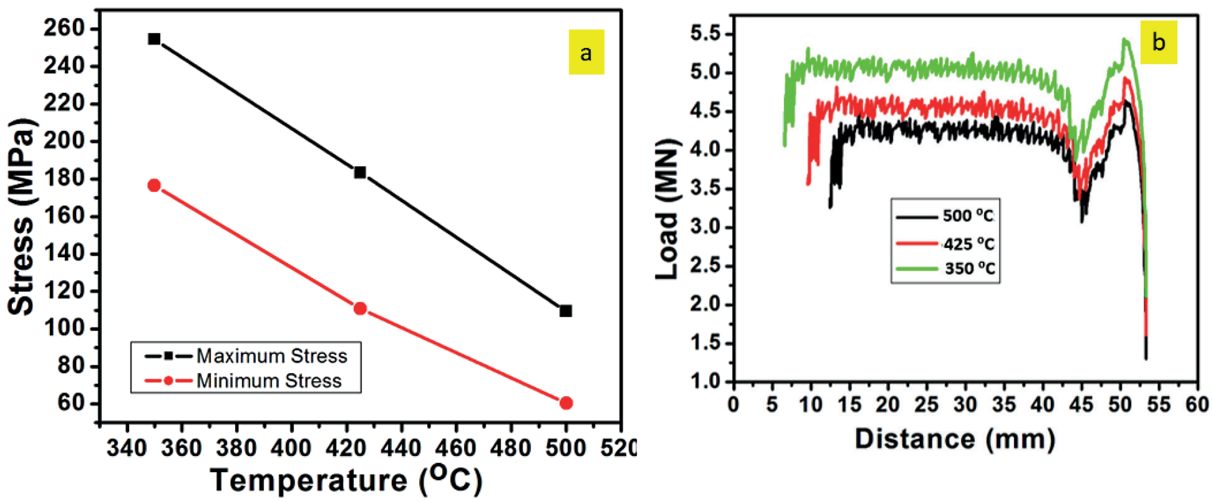

Figure 5. (a) Flow stress vs extrusion temperature (b) Load vs ram displacement curves for extrusion performed with a die angle of 130° at various temperatures

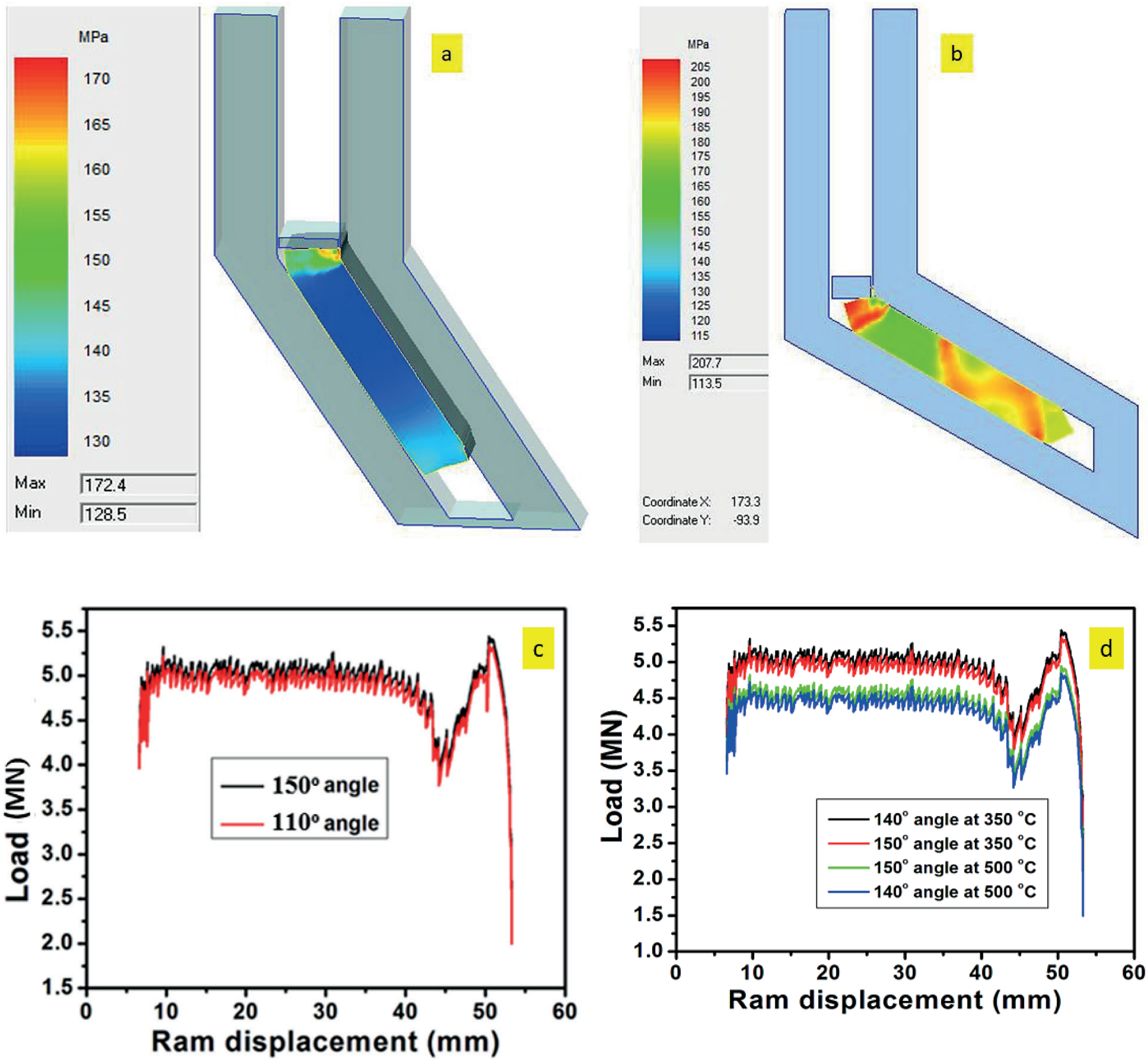

Figure 6. Extruded sample flow stress at 350 °C with a die angle of (a) 150°, (b) 110°, (c) the extrusion load-displacement curve at different die angles, (d) curves for the load-ram displacement during extrusion using die angles of 140° and 150° at two temperature ranges

Extruded and parent sample microstructural examination

Figure 7 displays optical microscope images for the original sample and extrudates surface texture. The grain transformation in a sample extruded at 350 °C (Figure 7b) compared to the original material (Figure 7a), showed no noticeable differences in micro-structural change. At 350 °C, both the parent aluminum 6063 and the aluminum that has been extruded have a coarse surface structure. At 500 °C, fine-grain microstructure development is observable (Figure 7c). This is because the development of subcells is a result of the increased dislocation volume caused by the high temperature, which refines the grains and is assumed to be the cause of the improved strength and hardness [5, 31-32].

CONCLUSIONS

This study established that, for all temperatures and angles taken into consideration, the temperature has a greater impact on ECAE process parameters than the die angle. However, the stress rose to its highest level of 184.7 MPa at die angle 110° from 172 MPa at die angle 150°. High temperatures can reduce the load required for extrusion to take place. It also made it possible for aluminum processed by ECAE to have a more homogeneous flow stress spread. Microstructural

Figure 7. Optical microscope images of (a) original Al 6063 specimen, (b) extruded Al 6063 at 350 °C, (c) extruded Al 6063 at 500 °C. Mag: ×1000

pictures show that the components extruded at a different temperature have smaller grains than the parent material.

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