

Effect of the cyclic expansion-extrusion process on mechanical properties and the grain refinement of AA6061 aluminum alloy

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Received 1 Mar. 2023; Revised 16 Apr. 2023; Accepted 18 Apr. 2023; Published 25 May 2023.

DOI: <https://doi.org/10.54939/1859-1043.j.mst.87.2023.100-107>

ABSTRACT

In this work, the cyclic expansion-extrusion (CEE) process for aluminum alloy AA6061 is due to its wide industrial applications. First, The CEE process is performed to create a fine stable grain size for the studied alloy. The microhardness of the deformed samples was determined to evaluate the effect of the CEE process on the mechanical properties of the alloy. The average microhardness of the deformed samples increased sharply after 1 CEE cycle from 40 Hv to 65 Hv or 68 Hv. It is particularly noticeable that in subsequent cycles, the average microhardness of the samples hardly changes (Hv ≈ 70). Subsequently, the microstructural survey was conducted to determine the average grain size of deformed samples. The average grain size reached about 5 ÷ 6 μm from the initial value of 100 μm after four CEE cycles. The results show that the effect of the cumulative strain of the CEEed samples significantly on the mechanical properties as well as for the grain refinement to create ultrafine grains (UFGs) in microstructures of the AA6061 alloy.

Keywords: CEE; Aluminum alloy AA6061; Microhardness; Microstructure; UFGs

1. INTRODUCTION

There are many methods to create ultrafine grains (UFGs) in microstructures for metals and alloys. Among them, severe plastic deformation (SPD) methods are widely used for industrial alloys [1-3]. Ruslan Z Valiev et al. [4] refer to the equal channel angular pressing (ECAP) method, which is known to be an SPD method to produce UFGs in the final microstructure. The outstanding advantage of ECAP is the ability to fabricate UFGs workpieces with a small average grain size. However, the workpiece size after each ECAP passes will be lost due to the removal of the front face of the workpieces for the next steps. Simultaneously, complex microstructural conditions of the material, such as grain boundary deviations and distribution of the second phase, must be controlled. Megumi Kawasaki et al. [5] proposed a SPD technique to fabricate nanostructured materials. The high-pressure torsion (HPT) method allows to fabrication of materials with fine grain structures with high strength. The HPT method can be applied to brittle materials, high strength materials at low temperatures that other methods are difficult to perform. The disadvantage of this method is that it often produces small-sized workpieces, and the uniformity of deformation in the radial direction is not high. Similar to the SPD methods mentioned above, multidirectional forging (MDF) is not only capable of making nanostructured workpieces of much larger size but is also simple in implementation and low in cost. However, in the process of making MDF, the intermediate steps often have to be reprocessed, so it takes time in the experimental process. Moreover, when forging in a closed die will lead to a sudden increase in forging force, making it difficult to choose testing equipment [6-8].

Cyclic extrusion compression (CEC) is one of the earliest developed SPD techniques. The CEC is often referred to as a reciprocating extrusion or cycle extrusion. A CEC cycle consists of two steps executed in succession. In the first step, the initial cylinder with a larger diameter is pressed through a die with a reduced cross-section. Next, the workpiece will flow to the cavity with a larger cross-section similar to the original injection die cavity [9, 10]. By performing successive extrusion cycles, a large degree of deformation of the workpiece can be obtained. Meanwhile, the size of the workpiece obtained through the intermediate steps does not change, which is an outstanding advantage compared to other techniques such as ECAP and MDF. The most important factor in making this method possible is the use of back pressure to shape the workpiece along the die cavity in the second step [9]. It is difficult to control the back pressure value because it is related to the deformation of the workpiece and the characteristics of the pressing device. Therefore, N. Pardis et al. [10] have proposed a new SPD method, which is improved from the CEC technique, called cyclic expansion-extrusion (CEE). Another feature of this new technique compared to CEC is that the cross-section of the die cavity used to extrude the workpiece is more expansive than the cavity containing the original workpiece. The pressure required to deform the workpiece to fill the expanded cavity is essentially equivalent to back pressure.

In this work, the cyclic expansion-extrusion (CEE) process for aluminum alloy AA6061 is due to its wide industrial applications. First, The CEE process is performed to create a fine stable grain size for the studied alloy. The microhardness of the deformed samples was determined to evaluate the effect of the CEE process on the mechanical properties of the alloy. The average microhardness of the deformed samples increased sharply after 1 CEE cycle from 40 Hv to 65 Hv or 68 Hv. It is particularly noticeable that in subsequent cycles, the microhardness of the samples hardly changes ($Hv \approx 70$). Subsequently, the microstructural survey was conducted to determine the average grain size of deformed samples. The average grain size reached about $5 \div 6 \mu\text{m}$ from the initial value of $100 \mu\text{m}$ after four CEE cycles. The results show that the effect of the cumulative strain of the CEEed samples significantly on the mechanical properties as well as for the grain refinement to create ultrafine grains (UFGs) in microstructures of the AA6061 alloy.

2. PROBLEM

2.1. Materials and methods

The aluminum alloy AA6061 was selected for the experimental process due to its impressive industrial properties. The original samples in the cast state are machined to the dimensions shown in Fig. 1a. The chemical composition of elements (in %wt.) consists of 1.044% Mg, 0.59% Si, 0.26% Cu, 0.371% Fe, 0.097% Mn, 0.141%Cr, 0.066% Zn, 0.037% Ti and balanced Al. The microstructure of AA6061 cast aluminum alloy is shown in Fig. 1b. The results show that the sample microstructure after casting has a dendrite structure. Aluminum alloys often have an unbalanced distribution around the grain. This microstructure adversely affects the mechanical properties and plasticity of the aluminum alloy. The initial samples after the tensile test are shown in Fig. 1c. The max relative elongation of the initial cast samples is about 10% at room temperature.

Fig. 2 shows the CEE process diagram of aluminum alloy AA6061 to prepare the microstructure with UFGs for SPF.

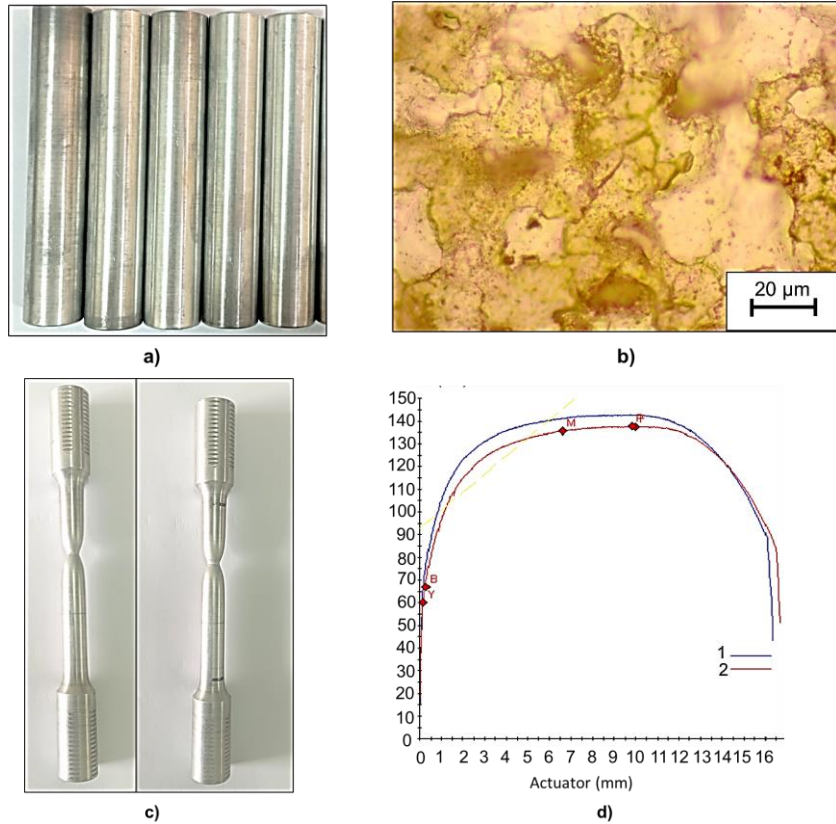


Figure 1. (a) The initial cast samples; (b) The microstructure of the initial sample; (c) The samples after the tensile tests; (d) The engineering stress-strain curve.

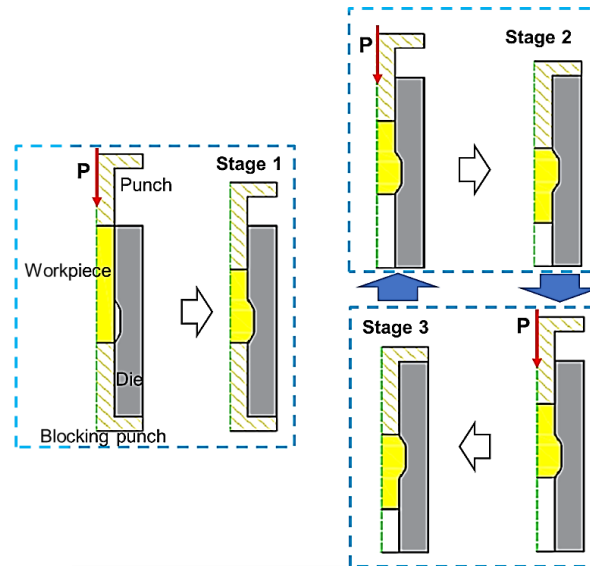


Figure 2. Diagram of the stages of the CEE process.

This process consists of three consecutive stages, where stage one is performed only once and stage 2 and 3 are performed sequentially through reciprocating extrusion. Stages two and three create a cycle of the CEE process. The initial samples are placed in the cavity of the die, its position limit is set by the fixed blocking punch. The primary punch

moves down and deforms the initial samples, the samples fill the expanded die cavity. The fixed blocking punch is removed before stage 2 is started. In stage 2, the primary punch continues to move downward, causing the workpiece to deform and flow from the expanded die cavity to the die with a smaller cross section. The pressure required to maintain the filling of the expanded cavity during the subsequent extrusion is the same as the back pressure in the CEC method [9, 10]. In stage 3, the bottom die and the deformed samples are rotated at an angle of 180 degrees, and the punch is held in the top position with the slide of the press device. Next, the extrusion process is carried out similarly to stage 2. From there, several cycles of the CEE process were performed in this study.

The material undertakes two portions of straining at expansion and extrusion. The theoretical strain ($\bar{\epsilon}$) that is accumulated in the material is then [10]:

$$\bar{\epsilon} = \ln \frac{D_1^2}{D_0^2} - \ln \frac{D_0^2}{D_1^2} = 4 \ln \frac{D_1}{D_0} \quad (1)$$

where D_0 is the initial workpiece diameter, D_1 is the diameter of the die extension.

2.2. Experimental process

The initial cylindrical samples with dimensions of 15 mm (diameter) x 80 mm (height) were used for the experimental process. Then, they were annealed in the LH120/13 Nabthem induction furnace at 425 °C for 3 hours and cooled in the furnace. The post-annealing samples are deformed in the mold according to the stages of the CEE process. The number of cycles of CEE process is performed from 1 to 4 cycles. The CEE process is carried out on a hydraulic press YH32, with a maximum pressing force of 100 tons, press speed range from 5 mm/s to 50 mm/s, and press stroke of 20 mm. The force of each press is determined through the pressure value applied to the hydraulic cylinder spindle displayed on the pressure gauges. Deformation tools and pressing devices and deformed samples are shown in Fig. 3.

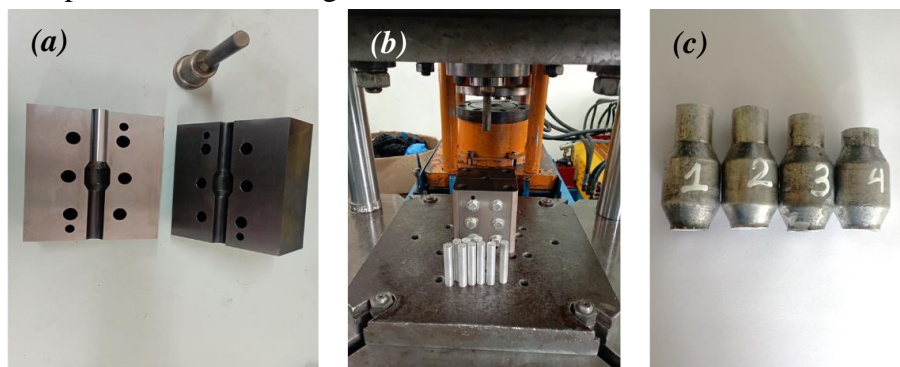


Figure 3. Deformation tools (a) and pressing device (b) of the CEE process; Deformed samples (c).

Samples before and after CEE were cut in cross-sections along the axis of the sample. The value of the Vickers microhardness, Hv, was measured in two directions: the horizontal direction and the vertical direction relative to the axis of symmetry of the samples. Microhardness measurements in each direction are made at 5 equally spaced points. The Mitutoyo Hardness test machine is used for the microhardness testing process.

The deformed samples by CEE were prepared for microscopic examination. They

were polished and etched with a solution Keller's Reage (95 mL water, 2.5 mL HNO₃, 1.5 mL HCl, 1.0 mL HF). The microstructural characterization of the samples was examined by an Axio Observer A2M Carl Zeiss optical microscope. The determination of the average grain size of the microstructure is done by Jeffris's method [12].

3. RESULTS AND DISCUSSION

The microhardness values measured in the two directions mentioned above are shown in Fig. 4 a, b. The measured hardness after 1 CEE cycle in the two directions mentioned above shows a significant heterogeneity, the hardness at the peripheral surface shows a significantly higher hardness than the hardness at the center of the deformed sample. This result is similar to the conventional extrusion process due to the effects of hardening and contact friction of the peripheral surface and the deformation tool. However, the microhardness values are relatively uniform between the measuring points in both the vertical direction and horizontal direction to the symmetry axis of the next CEE cycles. Thus, it can be estimated that the hardness uniformity in a deformed sample increases with an increasing number of CEE cycles. This result is explained by the increase in the amount of accumulated strain over the CEE cycles, leading to the saturation of the microhardness value of the aluminum alloy AA6061 [11, 12].

As shown in Fig. 4, it was found that the average microhardness of the deformed samples increased sharply after 1 CEE cycle from 40 Hv to 65 Hv or 68 Hv. Thereafter, there was a negligible increase after the 2 CEE cycle. It is particularly noticeable that in subsequent cycles, the microhardness of the samples hardly changes (Hv ≈ 70). This result is explained by the hardening after 1 CEE cycle, so the average microhardness of the deformed samples increases significantly. The accumulated strain over subsequent CEE cycles results in small change in the average microhardness. This is one of the important characteristics of SPD methods that affect the mechanical properties of materials [2].

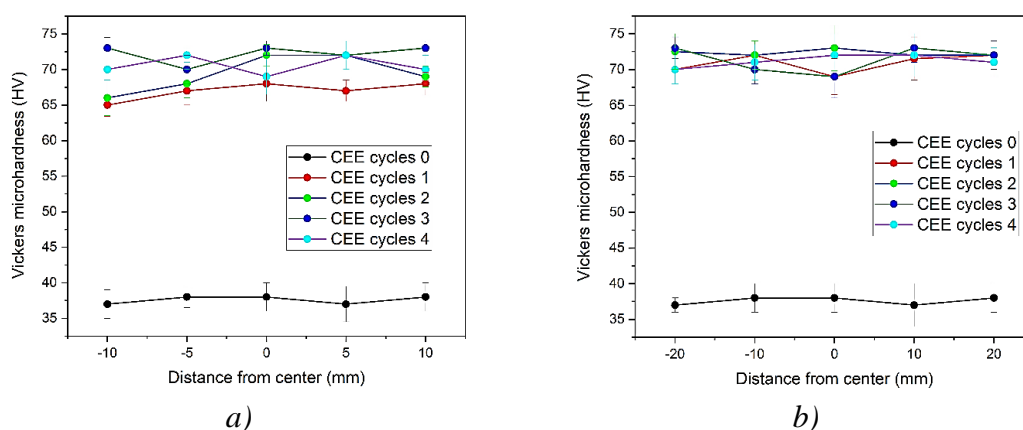


Figure 4. The average microhardness in the horizontal direction (a) and the vertical direction (b) relative to the axis of symmetry of the samples, for 1 or 4 CEE cycles.

The microstructures of the CEEed samples are shown in Fig. 5 and Fig. 6. The microstructures were also surveyed in two cross-sections: vertical and horizontal. After the 1 CEE cycle, the crystal grains tend to elongate in the direction of the symmetry axis of the CEEed samples, which coincides with the direction of the deformed force. At the same time, the crystal grains of the horizontal direction are also similar to the vertical

direction. This is true during stage 1 of the CEE process. The sample is deformed and bulged according to the expanded die cavity. The grains will be stretched, the expansion is deformed similar to the traditional upsetting. In the subsequent CEE cycles, we find that with the increase of accumulated strain, the crystal grains tend to split to form grains with smaller average grain sizes.

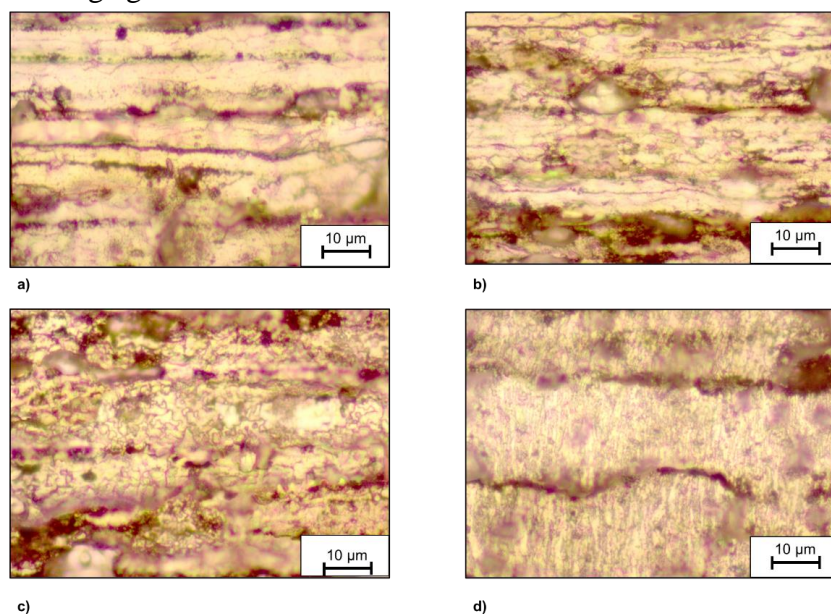


Figure 5. The microstructures of the AA6061 alloy after CEE cycles of vertical direction with (a) 1 cycle, (b) 2 cycles, (c) 3 cycles, (d) 4 cycles.

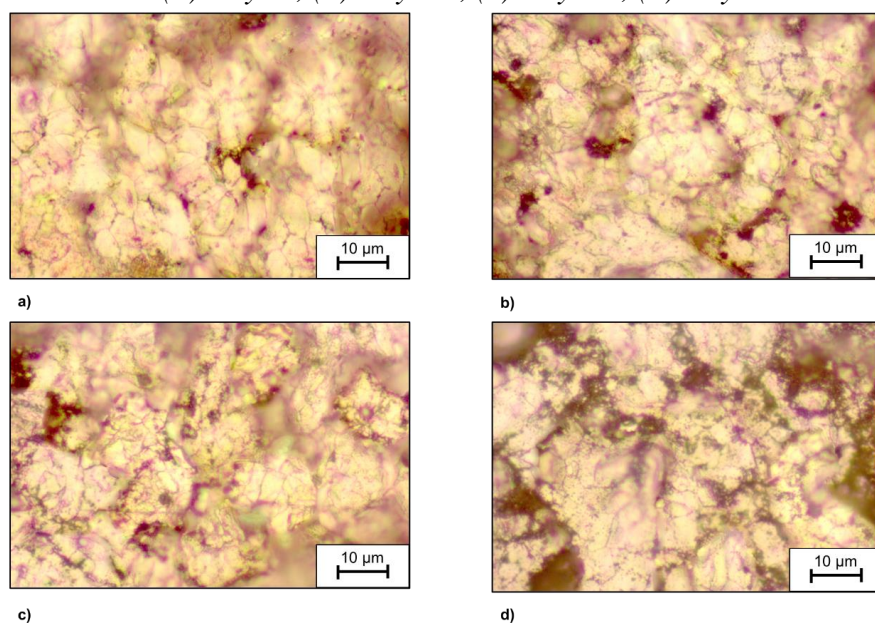


Figure 6. The microstructures of the AA6061 alloy after CEE cycles of horizontal direction with (a) 1 cycle, (b) 2 cycles, (c) 3 cycles, (d) 4 cycles.

The results showed a significant reduction in average grain size after 4 cycles of the CEE processes. The initial average grain size of the samples after annealing was 100 μm , and the

average grain sizes after 1, 2, 3 and 4 cycles obtained were $11.3 \pm 0.05 \mu\text{m}$, $9.3 \pm 0.03 \mu\text{m}$, $7.0 \pm 0.02 \mu\text{m}$ and $5.3 \pm 0.01 \mu\text{m}$, respectively. The uniformity of the average particle size of microstructures was also observed in both examined directions. These are also consistent with the microhardness distribution of the CEEed samples determined in Fig. 4.

4. CONCLUSIONS

In this study, the results indicate that:

- The cyclic expansion-extrusion (CEE) method is selected and experimentally conducted for aluminum alloy AA6061. The die structures and the implementation processes are simple, reducing the cost of the experimental process. The average microhardness distribution and microstructure of the alloy were determined to evaluate the ability of this SPD method.

- The CEEed samples showed uniformity in average microhardness after subsequent CEE cycles. The average microhardness distribution by volume of CEEed samples is an important factor in determining the large cumulative deformation ability of the studied method. This opens up the possibility of increasing the number of CEE cycles for research alloys for the fabrication of materials using SPD. The results allow for obtaining excellent properties of the alloys from the initial casting products.

- The average grain size in the microstructure of the studied alloy was obtained at about $5 \mu\text{m}$ after 4 CEE cycles. The obtained results are in agreement with previously published studies.

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TÓM TẮT

Ảnh hưởng của quá trình ép phình theo chu kỳ (CEE) đến đặc tính cơ học và tinh chế hạt của hợp kim nhôm AA6061

Trong nghiên cứu này, quy trình ép phình theo chu kỳ (CEE) cho hợp kim nhôm AA6061 do các ứng dụng công nghiệp rộng rãi của nó. Đầu tiên, quá trình CEE được thực hiện để tạo ra kích thước hạt mịn ổn định cho hợp kim nghiên cứu. Độ cứng tế vi của các mẫu bị biến dạng được xác định để đánh giá ảnh hưởng của quá trình CEE đến tính chất cơ học của hợp kim. Độ cứng tế vi trung bình của các mẫu biến dạng tăng mạnh sau 1 chu kỳ CEE từ 40 Hv lên 65 Hv hoặc 68 Hv. Điều đặc biệt đáng chú ý là trong các chu kỳ tiếp theo, độ cứng tế vi trung bình của các mẫu hầu như không thay đổi ($Hv \approx 70$). Sau đó, khảo sát tổ chức tế vi được tiến hành để xác định kích thước hạt trung bình của các mẫu. Kích thước hạt trung bình đạt khoảng $5 \div 6 \mu m$ từ giá trị ban đầu $100 \mu m$ sau 4 chu kỳ CEE. Kết quả cho thấy biến dạng tích lũy của các mẫu sau CEE ảnh hưởng đáng kể đến đặc tính cơ học cũng như quá trình tinh chế hạt để tạo hạt siêu mịn (UFGs) trong tổ chức của hợp kim AA6061.

Từ khoá: CEE; Hợp kim nhôm AA6061; Độ cứng tế vi; Tổ chức tế vi; UFGs.