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EVALUATION OF SUPERPLASTIC PROPERTIES OF AA7075 ALUMINUM ALLOY SHEET FABRICATED BY THERMOMECHANICAL PROCESSING

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Abstract: The superplastic forming (SPF) process is the large plastic deformation ability of metals and alloys. However, SPF ability can only be achieved under certain conditions including ultrafine grain (UFG) microstructure, high temperature, and very small strain rate. In this work, the high-strength aluminum alloy AA7075 was selected for the experimental process due to its outstanding industrial application. First, thermomechanical processing (TMP) is performed to create a fine stable grain size for the studied alloy. The UFG microstructure was obtained after TMP with an average grain size of about 10 µm. Subsequently, the tensile test method and the bulging free-forming (BFF) method were used to evaluate the superplastic properties of the AA7075 aluminum alloy sheet fabricated by TMP. These two methods are performed at temperatures of 500°C and 530°C with strain rates from 10^{-4} (s^{-1}) to 10^{-3} (s^{-1}). The relative elongation and the strain rate sensitivity are the evaluation criteria. At the temperature of 530ºC and strain rate of 10^{-3} (s^{-1}), the maximum relative elongation and flow stress were achieved at 280% and 7.6 MPa, respectively. The value of the coefficient m ranges from 0.3 to 0.6. The obtained results confirm the SPF properties of the aluminum alloy sheet AA7075.

Key words: Thermomechanical processing, high-strength aluminum alloy, ultrafine grain, strain rate sensitivity, superplastic forming.

1. INTRODUCTION

The SPF process is a special forming technology with outstanding advantages in creating very high deformability for industrial alloys [1,2]. This high deformability is useful in making complex, high-strength parts that cannot be achieved by traditional forming methods. To meet the SPF process, it is necessary to have strict conditions on microstructure, deformation temperature, and strain rate [3,4]. The superplastic materials must have an ultrafine grain (UFG) microstructure and uniform (usually between 5 and 15 µm) and grain size as unchanged during deformation time. The SPF temperature is in the range of 0.7 to 0.9 melting point of the deformed alloys. In addition, the SPF processes are performed at relatively slow strain rates, usually between 10^{-4} s^{-1} and 10^{-2} s^{-1}. The flow stresses of the SPF processes are usually low (usually<10 MPa) together with the stability of plastic flow, giving the outstanding advantages of SPF processes in industrial production. However, because the above conditions must be met, it will complicate and prolong the time of the SPF technology processes.

The microstructure with UFGs of alloys is one of the necessary conditions for the SPF process besides the conditions of high deformation temperature and low strain rate. There are many methods to create UFGs in microstructures for metals and alloys. Among them, the severe plastic deformation (SPD) methods and the TMP methods are widely used for alloy sheets [3,5-7]. Ghalehbandi et al. [8] refer to the accumulative roll bonding (ARB) method, which is known to be an SPD method to produce UFGs in the final microstructure. The outstanding advantage of ARB is the ability to fabricate UFG sheets with large sizes, including laminated sheets by cyclic cumulative strain. However, the surface quality of sheets and the heterogeneity of the different materials will greatly affect the superplastic properties of the final product. Jianyu Huang et al. [9] proposed a new SPD technique to fabricate nanostructured materials. The repetitive corrugation and straightening (RCS) method allows the production of metal sheets with UFGs in large quantities. The disadvantage of this method is that it often produces a sheet with poor surface quality after many deformation cycles and straightens the sheet before SPF.

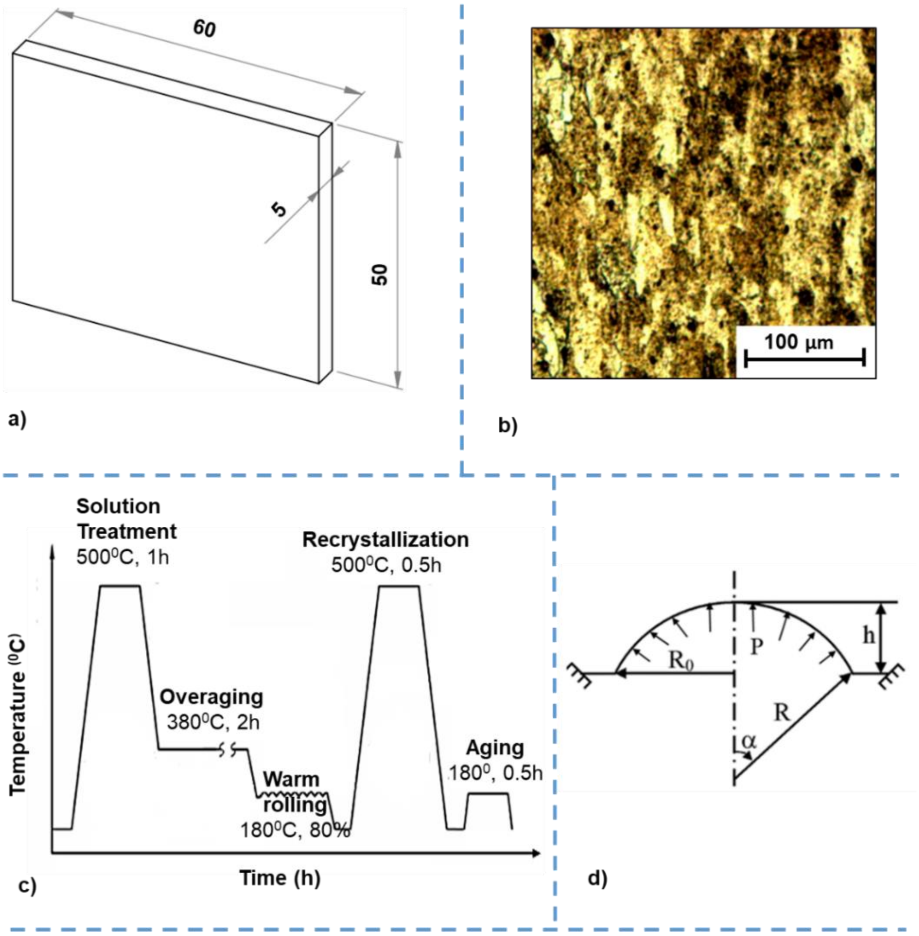
TMP is more widely used to create UFGs in microstructure for alloy sheets such as aluminum alloys for SPF. The advantages of this method compared with SPD are that the process is simple, the equipment conditions are not high, and the surface quality of the sheets is guaranteed. The disadvantage of TMP is that the processing time is often large. Therefore, Tahar Sahraoui et al. [10] presented a new TMP for aluminum alloy AA7075. The process is a continuous combination of the different stages in the process. This modified method by Taharsahraoui provides a significant improvement in process time.

There are many methods to evaluate the superplastic properties of AA 7075 aluminum alloy sheets. The most common is the tensile test method and the bulging free-forming (BFF) method [11,12]. Tensile tests under the conditions of strain rate and deformation temperature of SPF processes to determine the relative elongation of the tensile specimens. Based on the relatively large elongation achieved as well as the value of the small flow stress to evaluate the superplastic deformation ability of the studied materials. This method is simple to implement and is suitable for most materials and different sample sizes. The BFF method is a process whereby metallic materials in fine-grained sheet form are gas-pressure bulged into dies at elevated temperatures [13,14]. Strain rate sensitivity (m) is one of the most important parameters that prove the superplastic properties of alloys. They are determined from the relationship between flow stress and strain rate of BFF tests. The forming processes at high temperature with a strain rate less than 10^{-4} (s^{-1}) have m-factor less than 0.3. The traditional forming processes with a strain rate greater than 10^{-2} (s^{-1}) have m-factor less than 0.3. The m-factor can reach a value of up to 1 under ideal SPF conditions. However, the maximum value of the m-factor is usually from 0.3 to 0.8 with a strain rate in the range of 10^{-4} s^{-1} $\div 10^{-2}$ s^{-1} [3,4].

In this work, the evaluation of superplastic properties was performed for the AA7075 aluminum alloy sheet fabricated by TMP. Superplastic properties of the studied alloy are evaluated through two criteria including the relative elongation and the strain rate sensitivity of the tensile test specimens and the BFFed specimens, respectively. The obtained results will confirm the SPF properties of the aluminum alloy sheet AA7075.

2. MATERIALS AND METHODS

The high-strength aluminum alloy AA7075 was selected for the experimental process due to its outstanding industrial properties [3,4]. The original workpieces in the cast state are machined to the dimensions shown in Fig. 1(a). The chemical composition of elements (in %wt.) consists of (5.33-5.37)% Zn, (2.32-2.36)% Mg, (1.3-1.34)% Cu, ($\leq$ 0.3)% Fe, ($\leq$ 0.22)% Cr, ($\leq$ 0.04)% Ti, ($\leq$ 0.024)% Mn, ($\leq$ 0.05)% Si and balanced Al. The microstructure of AA7075 cast aluminum alloy is shown in Figure 1b. The dendrite structure was observed in the microstructure of the post-cast specimens. Aluminum alloys often have an unbalanced distribution around the grain. This microstructure adversely affects the mechanical properties and plasticity of the aluminum alloy. The relative elongation of the initial cast workpieces is about 10 % at room temperature.



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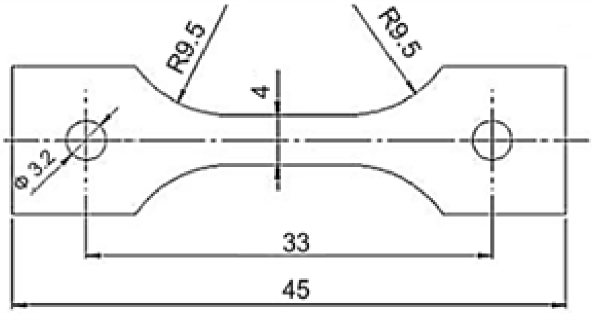

Fig. 1. (a) The initial cast specimens, (b) the microstructures of the initial specimens, (c) the TMP of aluminum alloy AA7075, (d) the schematic diagram of the BFF method, (e) the original tensile test specimen

Figure 1c shows the TMP diagram of aluminum alloy AA7075 to prepare the microstructure with UFGs for SPF. This process consists of five consecutive stages: solution treatment, overaging, warm rolling, recrystallization, and aging. This TMP scheme differs from the previously published TMP in the continuity of the stages. In the first 3 stages, the latter is performed at the termination temperature of the previous stage. The last two stages including recrystallization and aging are performed similarly. It is these distinctive features that make the time for the applied TMP to be significantly reduced. The workpiece is cooled in an aqueous medium immediately after the last stage of the TMP to obtain UFGs in microstructure for aluminum alloy AA7075. The scanning electron microscope (SEM-NANOSEM450) and optical microscope (AXIOVERT-25C) are used to study the microstructure the alloy sheet AA7075.

Tensile test specimens are machined from an aluminum alloy sheet after TMP with a thickness of 1.2 mm. The original tensile test specimens have dimensions as shown in Figure 1e, manufactured according to ISO 6892-1:2016 standard. These specimens are tested in the superplasticity condition for aluminum alloy AA7075 at 500°C and 530°C with strain rates of 5.10^{-4} (s^{-1}), 10^{-3} (s^{-1}), and $1.5.10^{-3}$ (s^{-1}). The device for the tensile testing process is the Devotrans DVT FU/RDNN 50kN - CKS testing machine. CKS-III software is used with the DVT DEVOTRANS tensile-compression test machines. TCP/IP protocol allows analysis of tensile test results according to selected standards, and easy export of test results reports. The electrical resistance furnace Nabertherm B180 is used to ensure the deformation temperature condition for the tensile specimens.

The BFF method is used to determine the strain rate sensitivity of aluminum alloy sheet fabricated by TMP. The schematic diagram of the BFF method is shown in Figure 1d. This method was chosen because of its suitability to the SPF conditions of the alloy sheet. Besides, this method makes it easy to process experimental specimens and does not require forming equipment with low machining speeds. The essence of this method is to determine the strain rate sensitivity through the height of the hemispherical part under the action of forming pressure at high temperatures. The experimental process was conducted at temperatures of 500°C and 530°C with different forming pressures at 0.6 MPa and 0.8 MPa. These values of forming pressure are determined based on the strain rate value of SPF conditions [3,4].

3. RESULTS AND DISCUSSION

The microstructures of the TMPed specimens are shown in Figure 2. Dissolution of all precipitates of the original workpieces was solution treated at 500°C. The formed large grain size particles are shown in Figure 2a. The purpose of overaging is to isolate grains of the second phase with a size of about 1 μm from the supersaturated solid solution obtained as a fast cooling process in water, which is observed in Figure 2b by SEM. In alloy AA7075, this is the S-phase (Al_2CuMg). Because of subsequent deformation (warm rolling at a temperature from 200°C to 220°C) in the zones adjacent to the specified grains, areas with an increased density of dislocations are formed. These sites serve as sites of preferred nucleation of grains during recrystallization. Thus, by selecting during heterogenization annealing uniformly over the entire volume of the S-phase particle, after rolling, many potential sites for the formation of grain nuclei are obtained. Figure 2c shows a subsequent recrystallization with the high heating rate which can form a UFG microstructure with an average grain size of approximately 10 μm. The grain size obtained after TMP meets the conditions of microstructure for the SPF process.

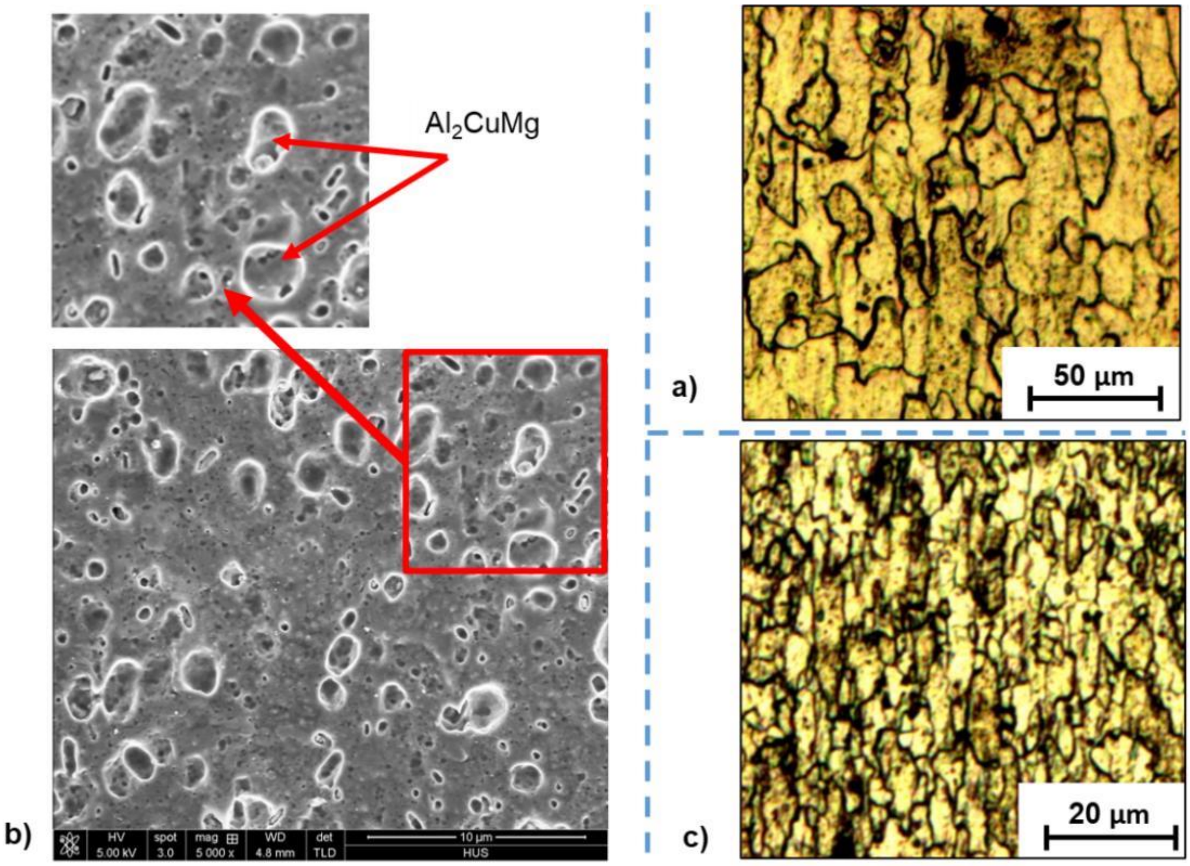

Fig. 2. The microstructures of the AA7075 alloy after the solution treatment (a), after the overaging (b), and after the TMP process (c)

Figure 3 shows the results of the tensile tests. According to Figure 3a, the deformed specimens at 500°C with strain rates 5.10^{-4} (s^{-1}), 10^{-3} (s^{-1}), and $1.5.10^{-3}$ (s^{-1}) are numbered 1, 2, and 3, respectively. Similarly, the deformed specimens at 530°C with strain rates 5.10^{-4} (s^{-1}), 10^{-3} (s^{-1}), and $1.5.10^{-3}$ (s^{-1}) are numbered 4, 5, and 6, respectively. Figure 3b and Figure 3c show the relationship between flow stress and relative elongation of tensile specimens at 500°C and 530°C with different strain rates. From this relationship, it can be seen that the relative elongation increases as well as the flow stress decreases when the deformation temperature increases. This is true for the physical properties of metals or alloys when deformed with high temperatures. The SPF process occurs at a high temperature which is usually higher than the recrystallization temperature of the alloy. Therefore, recrystallization is completely achieved. The result of hot deformation is that the metal receives a complete isoaxial recrystallization microstructure without the existence of hardening [3,4]. The ductility of the alloy will be significantly improved. The maximum elongation achieved in the tensile specimen at 500°C and strain rate of 10^{-3} (s^{-1}) is 240% compared with 280% in the tensile specimen at 530°C and strain rate of 10^{-3} (s^{-1}).

Through Figure 3b and Figure 3c, it is noticed that the relative elongation of the tensile specimen increases, and the flow stress increases when the strain rate increases from 5.10^{-4} (s^{-1}) to 10^{-3} (s^{-1}). But the when strain rate continues to increase from 10^{-3} (s^{-1}) to $1.5.10^{-3}$ (s^{-1}), the elongation of the tensile specimen decreases. These results can be explained by the strain rate being too large and not enough time for the amplification process to occur. The corresponding canopy creates planes that are favorable for sliding so that the flow stress increases and the elongation of the tensile specimen decreases [5, 15].

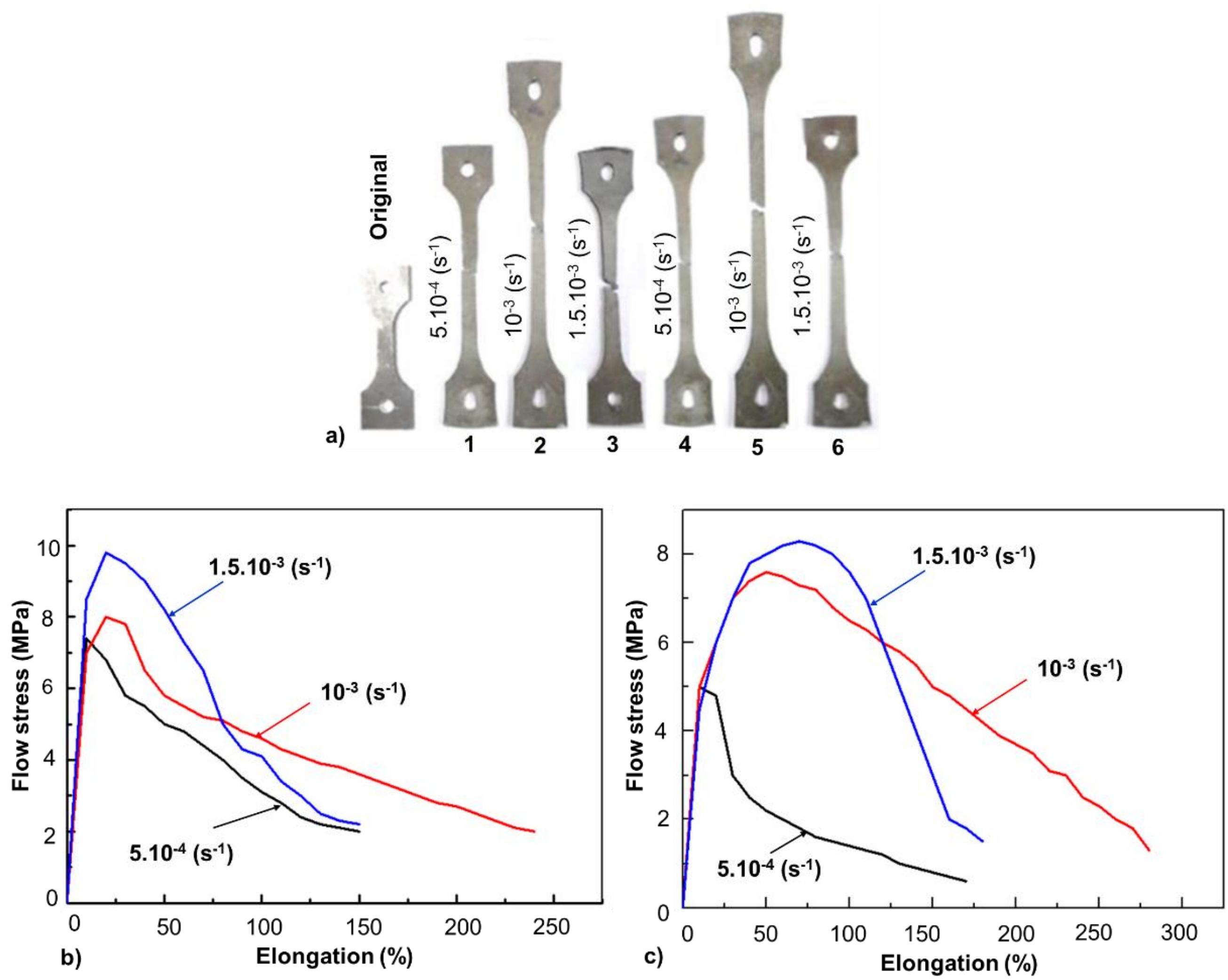

Fig. 3. (a) the deformed specimens; (b) the relationship between flow stress and relative elongation of tensile specimens at 500°C with different strain rates; (c) the relationship between flow stress and relative elongation of tensile specimens at 530°C with different strain rates

The AA7075 aluminum alloy sheet after the TMP process was machined into the specimens with a diameter of 50 mm for the BFF tests. The hemisphere details obtained after the BFF tests are shown in Figure 4a. The compressed air supply system includes a high-pressure Argon gas tank (P_{max} = 15 MPa), forming gas pressure regulating valve assembly (P_{max} = 2.5 MPa), and a compressed air pipeline. The height of the hemisphere is determined by the stroke sensor, which is shown in Figure 4b. The graph of the relationship between the height of the hemisphere and the forming time with different forming pressures at 500ºC and 530ºC are shown in Figure 4c and Figure 4d. It can be seen that the curve of hemispheric height over time can be divided into two periods. In the first stage, a linear similarity relationship is established. The increase in the slope of this curve corresponds to increased strain rate values. In the second stage, a sudden increase in hemisphere height is observed over time. Along with the deformation of the hemispherical part, there is a thinning of the material, especially the top of the hemisphere, so the height of the hemisphere is increased suddenly in a short time. As the pressure increases, the deformation ability of the alloy increases and thus forming time decreases.

Based on the data obtained from the graphs in Figure 4c and Figure 4d, the relationship between strain rate sensitivity and strain rate in BFF tests at different forming pressures was determined with deformation temperatures at 500°C and 530°C. Figure 4e and Figure 4f show that the strain rate sensitivity curve will shift to the part with a higher strain rate corresponding to a higher forming pressure (0.8 MPa). Besides that, when the deformation temperature is increased, with the same value of forming pressure (0.6 MPa or 0.8 MPa), the curve of strain rate sensitivity also moves to the part with a higher strain rate and larger value. It was found that with the TMPed AA7075 alloy sheet, the strain rate sensitivity in the BFF tests with different forming pressures and temperatures is greater than 0.3 at a strain rate in the range $5.10^{-4} \div 1.5.10^{-3}$ s^{-1}. The maximum value of sensitivity to strain rate achieved of 0.5 and 0.6 at deformation temperatures of 500°C and 530°C, respectively.

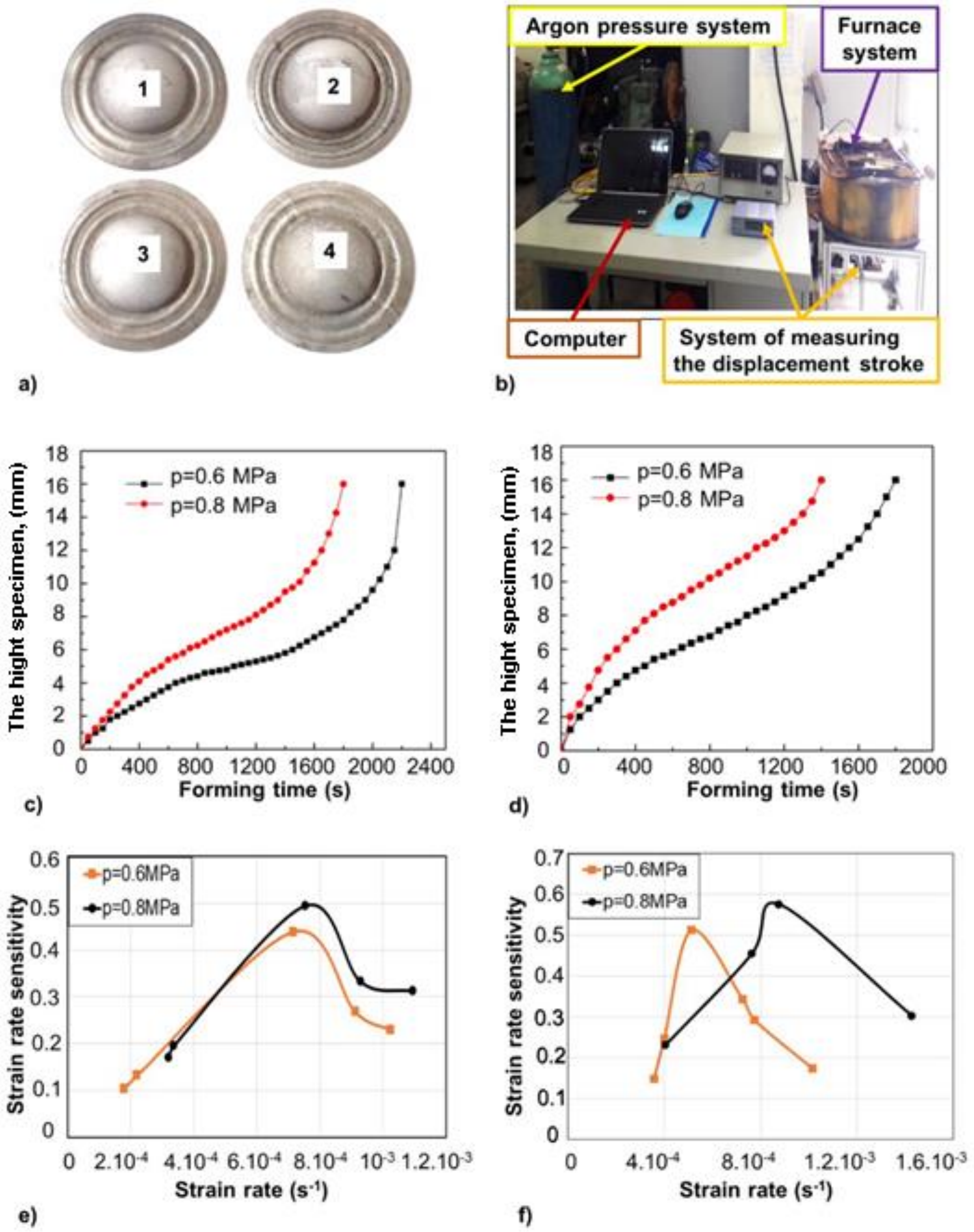

Fig. 4. (a) The hemisphere details after the BFF tests, (b) the equipment system for BFF tests, the curve of hemispheric height over time and the strain rate sensitivity with different forming pressures at 500˚C (c, e) and 530˚C (d, f)

4. CONCLUSIONS

In this work, TMP is performed to fabricate an aluminum alloy sheet AA7075 with UFGs for SPF. The average grain size in the microstructure of the studied alloy was obtained at about 10 µm. The microstructure of the TMPed alloy sheet AA7075 meets the conditions for the SPF process in addition to the factors of deformation temperature and strain rate. The tensile test method and the BFF method were used to evaluate the superplastic properties of the AA7075 aluminum alloy sheet fabricated by TMP. These tests were carried out at deformation temperatures of 500ºC and 530ºC with different strain rates of 5.10^{-4} (s^{-1}), 10^{-3} (s^{-1}), and 1.5.10^{-3} (s^{-1}). At the temperature of 530ºC and strain rate of 10^{-3} (s^{-1}), the maximum relative elongation and flow stress were achieved at 280% and 7.6 MPa, respectively. The maximum value of sensitivity to strain rate achieved of 0.5 and 0.6 at deformation temperatures of 500ºC and 530ºC, respectively. The obtained results confirm the superplastic properties of the studied alloy. The improvement of the average grain size in the microstructure of the alloy sheet AA7075 by the SPD methods and the optimization of the SPF processes will be studied in the future.

Conflicts of Interest: There is no conflict of interest.

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