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Original Article

Study on Cold Forging Process Design for Automotive Components of Al 6061 Alloys

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Abstract - *The present study was conducted to develop forgings for automobiles by increasing the cold forging formability of the Al6061 material. Heat treatment was performed at the temperatures of 350°C, 375°C, 400°C, 425°C, 450°C, 475°C, and 500°C to evaluate the formability of the raw material depending on the heat treatment conditions. Tensile test specimens were prepared for each heat treatment condition, and their tensile strength, yield strength, and elongation were measured through a tensile test. The test results showed that the maximum elongation and the minimum yield strength, indicative of the highest formability, were found at 400°C. The flow stress and fracture damage were calculated by using the displacement-load relationship obtained from the tensile test. Multi-stage forging process was designed, and forming process analysis was performed. In the forming analysis of products with a large flange and a small thickness, a value equal to or less than the limiting damage was predicted. A prototype forming was performed through the designed forging process, and as predicted by the finite element analysis, no forging defect occurred. It was confirmed that in the forging process with a large amount of deformation, forming limits can be increased through heat treatment of raw materials, and defects can be avoided.*

Keywords - *Aluminum alloys, Annealing treatment, Flow stress, Cold forging, Forging defects, Finite element analysis.*

1. Introduction

Aluminium is widely used for electric facilities, such as power cables, automobiles, and household electric appliances since it is light and strong and has high electric conductivity and high corrosion resistance. Aluminium alloys of 2000 to 7000 series, prepared by adding copper, manganese, silicon, magnesium, and zinc to the pure aluminium 1000 series, are widely used. Different series of aluminium alloys have different strengths and uses and undergo different heat treatment methods. The aluminium alloys of series 2000, 6000, and 7000 are often subjected to T6 heat treatment in which solution treatment and aging are carried out to increase the strength through the precipitation of fine grains of the alloy elements. With the lightweighting trend of automobiles, the scope of using aluminium alloys in the car body and underside components is expanding, and a fastener, which connects the car body with the components, is within the scope of application. Automotive fasteners have a wide range of materials to choose from, ranging from AISI 1010 mild steel to AISI4140, depending on the strength. Components made of aluminium materials are replacing mild steel products, which have a low strength. For automotive components, the aluminium 60xx series, which has excellent formability and can easily achieve large deformations, is widely used as a forging material.

This is because it has a relatively high strength among the 60XX series materials, and the strength may be improved by precipitation hardening through aging in the T6 heat treatment. In addition, it is a material that has high resistance to stress corrosion, excellent extrusion properties, and proven formability, and thus is widely used in automotive components [1]. Aluminium alloys have lower formability than steel materials and may not be subjected to spheroidizing annealing to increase formability, like steel materials. Therefore, there is the risk of forging cracks caused by cold forging due to low formability [2-4]. Therefore, a study is required about the heat treatment conditions for increasing the formability of drawn aluminium rods. Al6061 alloys, having good forgeability and processibility, undergo various forming processes to implement a form, and their mechanical properties are improved through T6 heat treatment, in which the alloys are finely distributed by a solution heat treatment and precipitated by artificial aging. Most previous studies have focused on the investigation of the increase of the mechanical properties through the final stage of T6 heat treatment and on the optimization of the mechanical properties depending on the heat treatment conditions [5-7]. However, the purpose of the present study is to increase the formability of the Al6061 material at room temperature in order to prevent the cold forging cracks of aluminium components.

Table 1. Chemical composition of Al 6061(wt%)

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Val.	0.4 - 0.8	0.7 max	0.15 - 0.4	0.15 max	0.8 - 1.2	0.04 - 0.35	0.25 max	0.15 max

Table 2. Tensile test results

Annealing Temp [℃]	Tensile strength [MPa]	Yield Strength [MPa]	Elongation [%]
F	177.56	129.10	25.91
350	155.55	115.83	26.48
375	152.51	111.67	27.49
400	152.74	111.06	27.70
425	159.56	117.27	27.17
450	160.35	118.31	26.86
475	168.99	122.91	26.60
500	171.28	124.26	26.51

To eliminate the solution treatment history, Al 6063 alloy is soaked at a temperature of 415℃ for 2 to 3 hours, cooled down to 260℃ at a rate of 28℃/h, and subjected to secondary cooling to room temperature at any rate. To remove the effects of cold work, the material is heated to 345℃ and then cooled [8]. Maisonnetteet et al. investigated the coarsening of the secondary precipitates due to reheating. They found that the average length and diameter of the precipitates were increased by over 250% and 64%, respectively, after the reheating to 400°C.

Compared to the T6-treated conditions, a strength decrease of about 60% was observed in the case of reheating [9]. Lee and Tang reported that the reheating of the AA 6061 alloy reduced the amount of dislocation, decreasing the strength and flow stress. When the reheating temperature was increased from 100˚C to 200˚, the flow stress was reduced by 9.3%, and a further reduction of 16% was found at a maximum temperature of 350˚ [10].

Khan et al. reported that the reheating of the T6-treated Al6061 from 200 ˚C to 343 ˚C resulted in a 21 % decrease in the strength [11]. As shown in the above study, the formability of aluminium alloys is affected by the heat treatment temperature. Hence, optimization of heat treatment conditions to increase formability is necessary to prevent forging defects in severe forming, such as cold forging.

In the present study, the annealing conditions for maximizing the cold formability of the raw material Al6061 alloy by eliminating the residual stress according to the manufacturing history were selected, and the optimal heat treatment conditions were determined through a tensile test. The flow stress was calculated by using the tensile test results to design a cold forging process, and the forming stability was evaluated based on the presence of forging defects through a finite element analysis. A prototype was manufactured through the proposed forging process to confirm the cold forging stability of the Al 60xx series.

2. Deformation Characteristics of Materials

2.1. Effect of Annealing Temperature on Materials

The material used in the present study was Al6061, which is an Al-MG-Si-based alloy. Table 1 summarizes the chemical compositions of the Al 6061 alloys. A previous report recommends annealing the Al 60XX alloys at 345°C to increase the cold forging formability [8]. In the present study, to evaluate the formability of the cold-drawn material, the heat treatment conditions were set to 350°C, 375°C, 400°C, 425°C, 450°C, 475°C, and 500°C for 2 hours.

Tensile test specimens were prepared according to the ASTM E8 subsize specifications. Figure 1 shows the shape of the specimens before and after the tensile test. The tests were performed with five specimens for each heat treatment condition. Table 2 and Figure 2 show the average tensile strength, yield strength, and elongation. The displacement and load curves of test tests are shown in Figure 3.

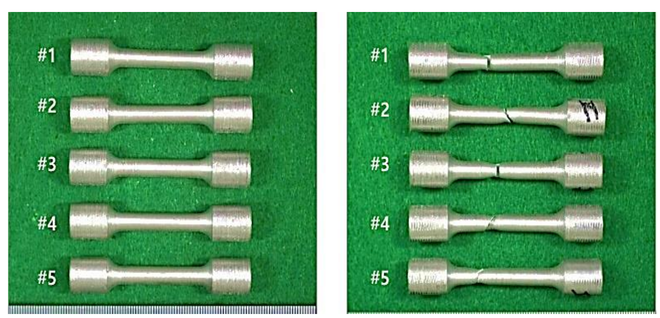

Fig. 1 Test specimens before and after the tensile test

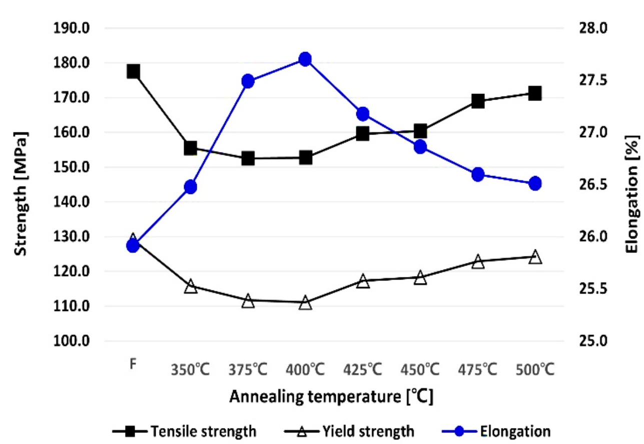

Fig. 2 Strength and elongation changes on heat treatment temperature

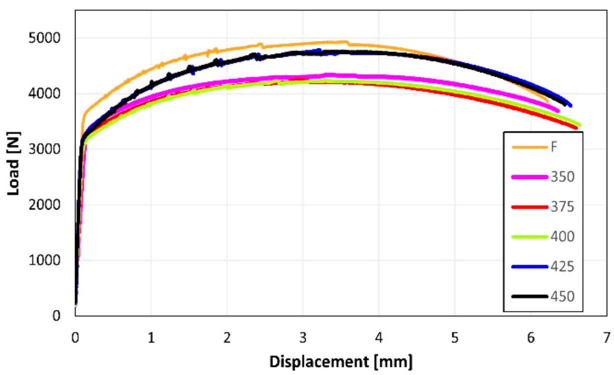

Fig. 3 Load-displacement curves on heat treatment conditions

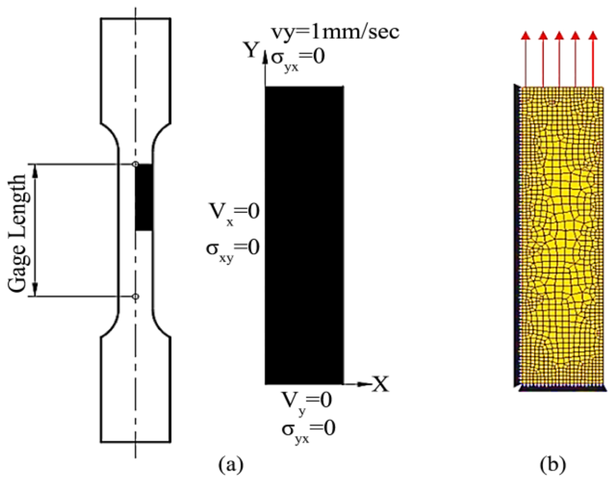

Fig. 4 FE analysis model boundary condition for tensile test

In Figure 3, the specimens at 375℃ and 400℃ x 2hr exhibited high elongation, low yield strength and tensile strength and thus are considered suitable for cold forging. The specimens of 375℃ and 400℃ showed similar results, but 400 ℃ showed a slightly greater elongation, so it was selected as the raw material heat treatment condition.

2.2. Calculation of Flow Stress

The flow stress and forming limit were calculated by using the tensile test results for the condition of 400℃ x 2 hr, at which the best formability was found. The calculation of the flow stress was carried out by using Deform 2D S/W with the inverse method so that the error between the tested load and the analytical load may be less than a certain value [12]. The flow stress was calculated by using the gauge length portion of the tensile test specimens. The calculation was performed such that the tensile load obtained from the finite element analysis and the tensile load obtained from the tensile test may coincide with each other. Figure 4 shows the model and the boundary conditions for the finite element analysis. The finite element analysis of the tensile test is to obtain the accurate flow stress. Figure 5 shows the distribution of the effective strain and damage of the tensile test specimens at the 40%, 90%, and 100% deformation using flow stress obtained through the inverse method. The consistency of the calculated flow stress was determined by the coherence between the load obtained from the finite element analysis and the load obtained from the tensile test. Figure 6 compares between the FE analysis load and the tensile test load. Figure 7 shows the flow stress obtained from the finite element analysis of the tensile test.

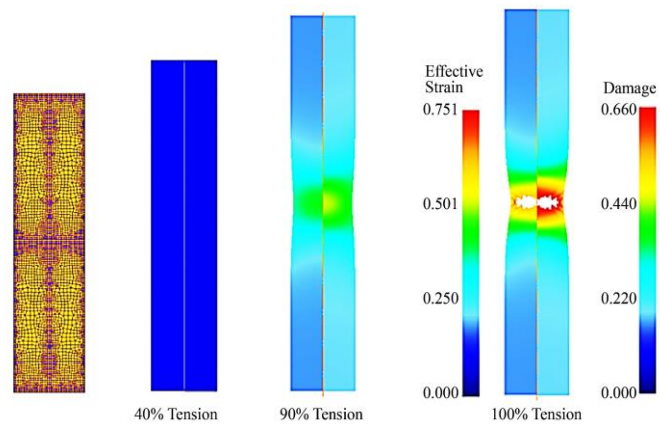

Fig. 5 Finite element analysis results of tensile test

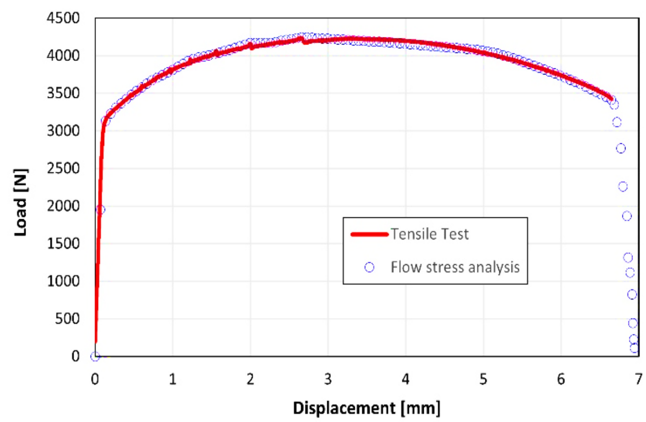

Fig. 6 Load comparison between tensile test and FE Analysis

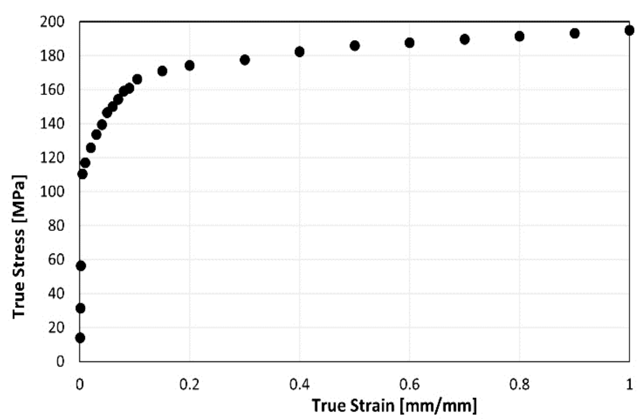

Fig. 7 True strain–stress curve calculated by the inverse method

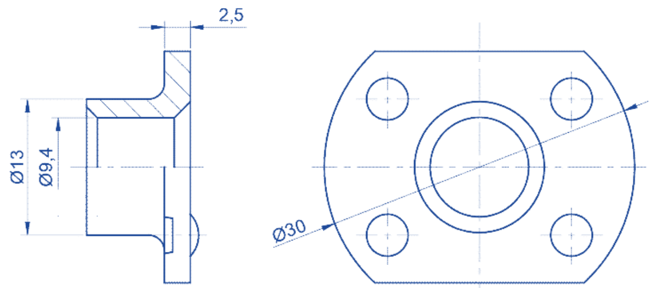

Fig. 8 Dimensions of automotive components

3. Cold Forging Processes of Al 6061 Alloys

3.1. FE Analysis of 1st Forging Process Design

The part of the present study is the automotive component, which is cold forged from mild steel. The present study was conducted to change the material from steel to Al6061 alloys. The product is a large and thin flange of a complicated shape with holes in the internal circumference, as shown in Figure 8. The cold forging process, which is being mass produced, is examined to predict the occurrence of forging defects such as folding and cracks, which may be generated when the Al6061 material is applied to the same process as the conventional steel materials. A finite element analysis of the conventional forging process (1st process) was performed by using the commercial Deform 2D/3D software program. For the flow stress of the material, the flow stress of the Al6061 material annealed at 400℃, as illustrated in Figure 7, was calculated and used as an input.

The product was produced in the multi-stage parts former machine with phosphate-treated Al 6061 alloys. Since the working fluid of the former served as a lubricant, a friction coefficient of 0.1 was used as an input. The forging die was assumed to be a rigid body for the sake of analytical convenience. The finite element analysis was performed using Deform 2D on the axi-symmetric conditions for the 1st and 2nd stages. The 3rd stage was mapped to a 1/4 3D model for the analysis. In the 3D analysis, the material was divided into 50,000 elements of a tetrahedral meshes.

Figure 9 shows the 1st forging process, which is the conventional forging process. After the forming shown in Figure 9, a coining stage is performed to obtain the final shape shown in Figure 8. Since the coining process is localized deformed for 4 steps, the finite element analysis was performed up to the 4th stage in which large deformations occur.

The results of the finite element method of the 1st forging process showed no forging defects in terms of shape, effective strain, and damage in the 1st, 2nd, and 3rd stages. In the 4th stage, however, since the boss portions were the same in the 3rd stage and the 4th stage and the shape inside the boss was deep, folding of the flange contacting die occurred in the final stage, and the damage value also reached 1.1. Therefore, the possibility of cracking was predicted. Figure 10 shows the forging shape, effective strain, and damage in each stage of the 1st forging process.

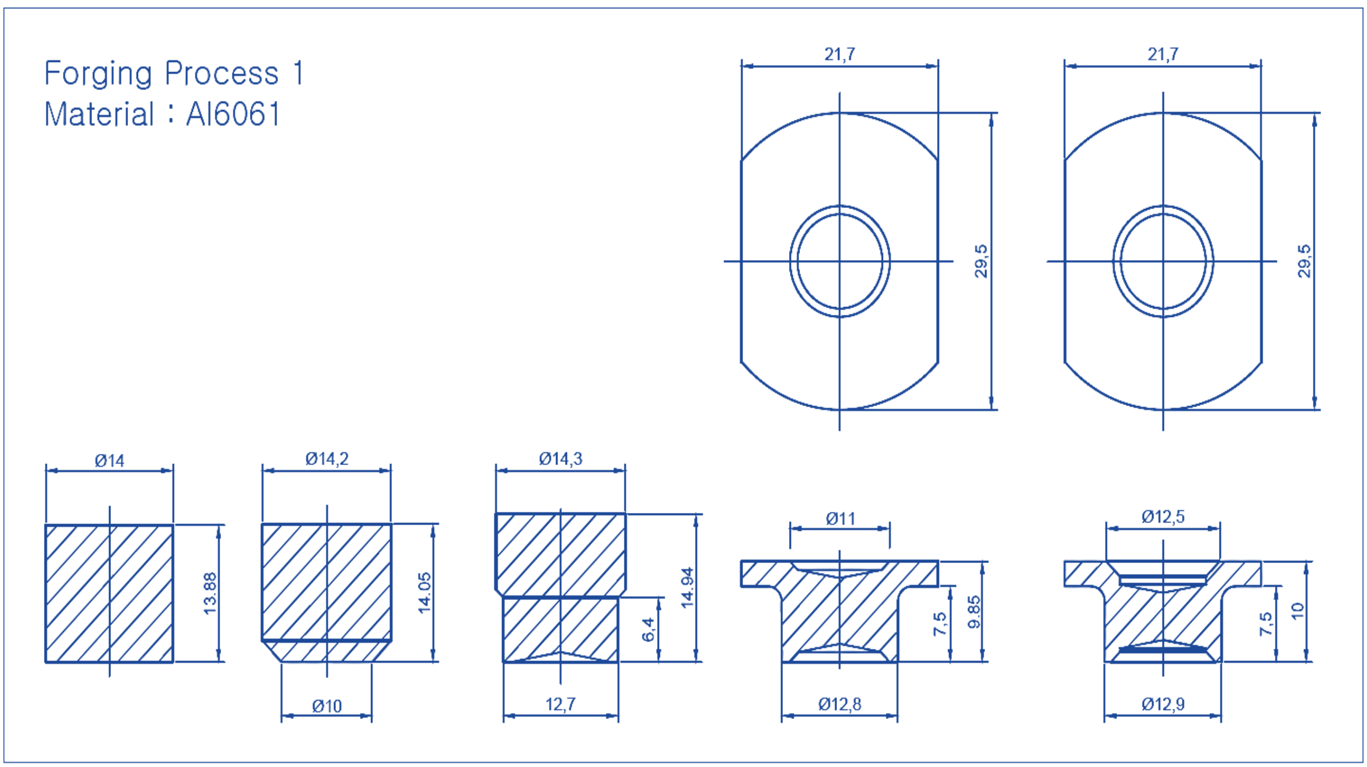

Fig. 9 Cold forging process design (Draft 1)

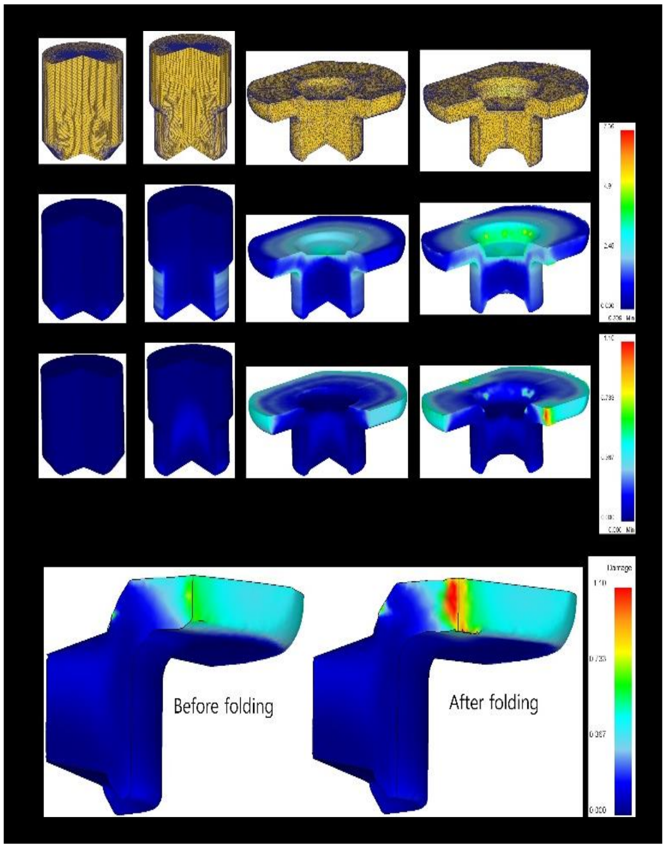

Fig. 10 Finite element analysis results of forging process (Draft 1) (a) Forging Shape, (b) Effective strain, (c) Damage, (d) Folding shape

3.2. FE Analysis of 2nd Forging Process Design

To solve the folding problem of the 1st forging process, the boss length of the 3rd process was changed to 7mm in the 2nd forging process. The 2nd forging process is shown in Figure 11. The forming analysis of the 2nd forging process predicted that the maximum damage value was 0.58 because the flange overlap phenomenon found in the 1st forging process did not occur. The filling of the flange outer diameter was completed when thickness forming was completed.

Since the fracture damage value of the raw material heat-treated at 400℃ was 0.66, it was predicted that no cracks would occur in the outer diameter of the flange. The forging shape, effective strain, and damage values of the 2nd forging process are shown in Figure 12.

3.3. Prototype Production

A forging tool was prepared by the 2nd forging process, which was predicted by the finite element analysis to avoid forging defects, to produce a prototype. Figure 13 shows the shape of the prototype formed by a multi-stage former in each stage of the process. No forging crack or folding was found at the outer circumference of the flange, at which the highest damage was predicted.

However, the trace of cutting on the cutting surface of the Al6061 alloy remained until the final product. This trace is not a forging defect and may be removed by changing the method of cutting the raw material from cropping to saw cutting.

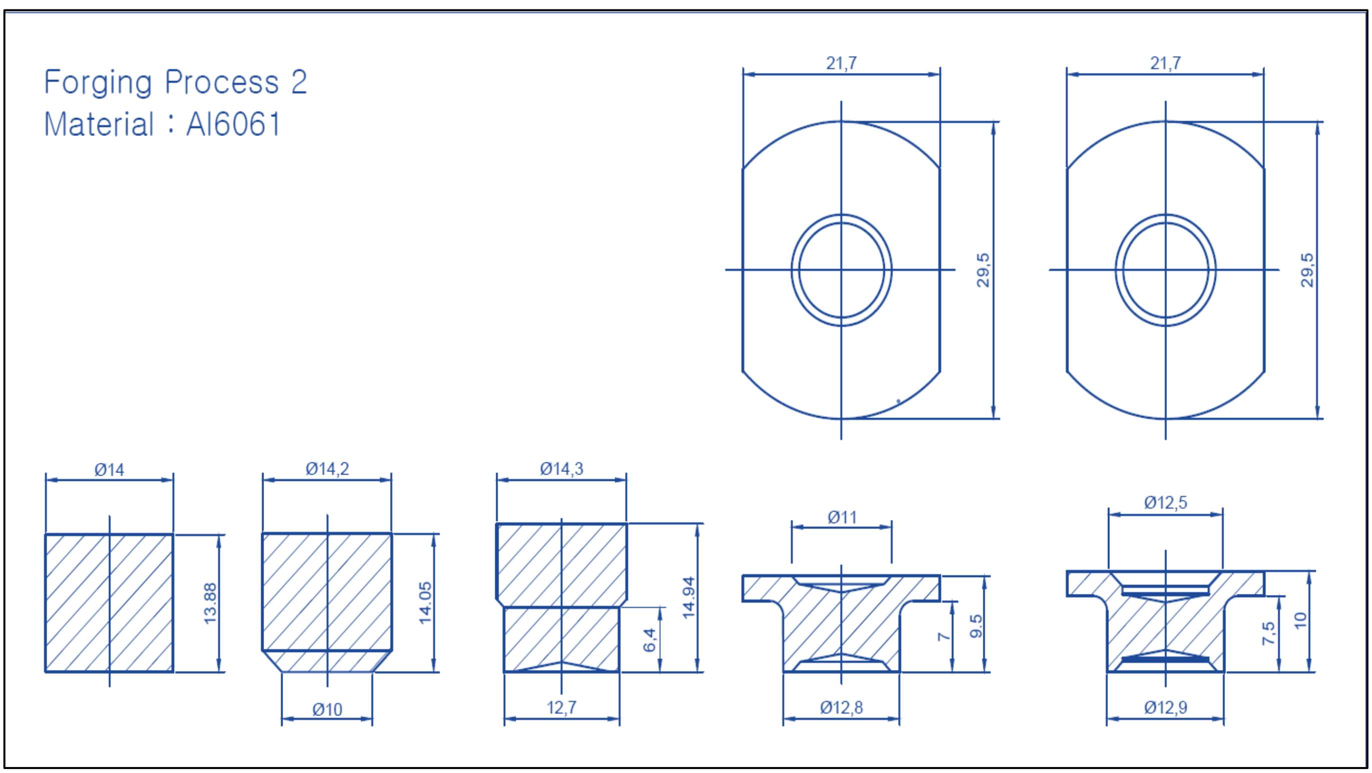

Fig. 11 Cold forging process design (Draft 2)

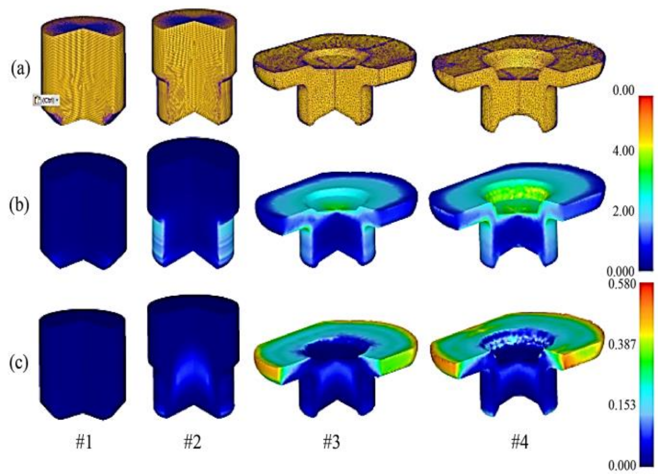

Fig. 12 Finite element analysis results of forging process 2 (a) Forging Shape, (b) Effective strain, (c) Damage

Fig. 13 Forged prototype by forging process (Draft 2)

4. Conclusion

The present study was conducted to form components of the Al6061 material by a cold forging process. A tensile test was performed at different heat treatment temperatures of the raw material, and the flow stress was calculated under conditions of excellent formability. In addition, the forging process was analyzed to produce a prototype. The following conditions were obtained from the results of the present study. With regard to the heat treatment for increasing the forgeability of the aluminum material, the maximum formability was found at 400℃, which was slightly higher than 345℃, the temperature suggested by a previous study. In the annealing of the aluminum material, the change of the tensile strength and yield strength was in the opposite direction of the change of the elongation, which was not different from the general metalogical theory. The fracture damage value of the Al6061 alloys obtained by a tensile test under the Temper O conditions was 0.66, which was slightly lower than that of the mild steel materials for forging.

However, the forging process is applicable to the forming of forged products without a complicated shape.It was confirmed that even with Al 6061 alloy, stable productivity can be achieved for products with flanges and a large deformation amount through appropriate heat treatment and forging process design.

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