Investigation of hot metal gas forming process of square parts

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Article info:

Abstract
Aluminum alloys are considered a lot in the automotive and aerospace industry because of their high strength to weight ratio. In this manuscript, the gas forming process of aluminum AA6063 tubes at high temperatures up to 500°C is investigated, through experimental and numerical tests. Therefore, an experimental setup is prepared and so, tube specimens are formed in a die with square cross section. Finite element simulation of the hot gas forming process is carried out to investigate the effects of process parameters including time period of forming process, temperature, and loading path. Uniaxial tensile tests under various temperatures and strain rates is performed, in order to obtain flow stress curves of the material. Corner radius and thickness distribution of tubular formed parts is investigated. The results show smaller corner radii could be formed at higher temperatures, whereas lower forming pressure is necessary. Increasing the time period of the process enhances the corners of the specimens to be formed. In addition, the maximum of formability is obtained when the gas pressure increases rapidly at the beginning of the process. However, the increasing rate of gas pressure must be reduced to form a smaller corner radius.

Keywords: Gas forming, High temperature, Aluminum, Square cross-section part, Corner radius.

Received: 00/00/2000
Accepted: 00/00/2018
Online: 00/00/2018

Nomenclature

K Strength coefficient
m Strain rate sensitivity index
n Strain-hardening exponent
έ Equivalent strain
dέ Equivalent strain rate
σ Equivalent stress

1. Introduction

The crisis of fuel consumption has emerged through 21st century. As vehicles are major fuel consumers, automotive and aerospace industries seek alternative ways to control the consumption of the fuel. One of the effective ways in this regard, is reducing the weight of vehicles. It also helps to decrease the air pollution and greenhouse gases [1]. Nowadays, there is a huge
competition to use the materials which have high specific strength in the automotive industry and other industries [2]. Aluminum alloys are widely used because of their high specific strength and also their capability for energy absorption. The high percentage of the alloying elements in aluminum alloys is the main reason of their low formability. Thus, the application of these materials is limited currently [3]. A proper way to solve this problem is to form these materials at higher temperatures [4].

The Warm Hydroforming (WHF) is a modern forming approach, which is used to form aluminum alloys in automotive industries. In recent years, the warm hydroforming process has been investigated by many researchers. Keigler et al. [5] investigated the formability, thickness distribution, and microstructure of the specimens, before and after the WHF process. Yi et al. [6] used a combined heating system, including an induction coil around the die and heating element located inside of the tube. Hi et al. [7] studied the deformation behavior of magnesium tubes AZ31B in both longitudinal and circumferential directions. Based on their results the longitudinal formability increases at high temperatures while the circumferential formability decreases at a specific temperature range. Hashemi et al. [8] investigated the thickness distribution of hydroformed aluminum tubes AA1050 at high temperatures and found that the thickness distribution uniformity increases at temperatures above 200°C. Kim et al. [9] simulated warm free bulge process of aluminum tubes using finite element code DEFORM-2D. They investigated heat transfer between the die and the tube. Hashemi et al. [10] predicted the Forming Limit Diagram (FLD) of aluminum tubes at high temperatures using modified ductile fracture criteria and Zener-Hollomon parameter in the simulation of WHF process. Abedrabbo et al. [11] developed a temperature-dependent anisotropic material model in the finite element analysis. Using this new model, forming process of two automotive aluminum alloys (i.e. AA5182-O and AA5754-O) from room temperatures up to 260°C was simulated. This developed thermo-mechanical constitutive model predicted accurately both the deformation behavior, and failure location in the blank.

Prior investigations show the hydroforming process could be applied only at room temperatures up to 300°C. This limitation is due to the lack of appropriate and efficient fluid at higher temperatures [12]. Thus, hydroforming process is limited to form the complex shape and large deformations. Moreover, cold hydroforming needs a higher pressure of fluid and as a consequence, bigger and more expensive tools and fittings. In order to overcome these limitations in the WHF process of aluminum and magnesium tubes at high temperatures (higher than recrystallization temperature), another fluid (air or inert gases such as argon, nitrogen, or carbon dioxide) must be used for applying internal pressure. This process is called Hot Metal Gas forming (HMGF). Naka et al. [13] investigated the effects of forming speed and temperature on the FLD in stretch-forming tests. The results showed that limit strain increased drastically with decreasing speed, while at room temperatures the FLD is not so sensitive to the speed. Also, improvements in the formability at 300°C and low forming speed is specifically due to the high strain-rate hardening characteristics, while below 200°C the formability is strongly affected by strain-hardening. Verma et al. [14] developed an FE methodology based on a two-mechanism material constitutive model to simulate the high-temperature forming of Mg AZ31 sheet. The FE simulations predicted the thinning of Mg sheet metals with reasonable accuracy. However, the material model fails to accurately track the forming rate near sheet rupture in the free-form bulge forming at the lowest gas pressure. HE et al. [1, 4] investigated the formability and microstructure of AA6061 aluminum alloys. In addition, fracture mechanism in HMGF for bulging aluminum tubes was studied at temperature ranges 350°C-500°C. The results showed the fracture mechanism at high temperatures was due to the accumulation of micro-pores. Also, three types of longitudinal fracture, peripheral, and random directions occur. Maeno et al. [15-16] investigated HMGF of aluminum tube to be bulged at elevated temperatures up to 400°C. They also investigated the effects of internal pressure, and intensity of the electric current on the expansion ratio. Results show the lower heat conduction of the die improves the corners filling. Lee et al. [17] studied the effect of material microstructure on the mechanical properties and formability of AZ31 alloys, by applying uniaxial tensile test at
room temperature and 400°C and biaxial tensile test at 400°C. They observed the twin density, dislocation density, and grain size are effective on the mechanical properties of AZ31 alloys at room temperatures. While, the mechanical properties are only affected by initial grain sizes in the temperatures higher than 400°C. Paul and Strano [18] investigated the effect of process parameters on the hardness and quality of the steel specimens produced by HMGF process. They observed that hardness is mostly dependent on pressure-temperature curve in areas which need calibration, moreover, hardness is dependent on tool temperature in the areas which contact quickly with the die. Wu et al. [19-20] formed Ti-3Al-2.5V titanium alloy tubular components with 70% expansion ratio, when the temperature differences are 0, 50, and 15°C using a non-uniform temperature gas forming experimental device. They examined the effect of temperature distribution on the deformation behavior, thickness, microstructure, and mechanical property of the material. Results show that a suitable temperature difference between forming zone and transition zone is beneficial for axial feeding, which promotes the thickness distribution uniformity. In addition, the best loading path to form tubular component was achieved at 800°C. Kim et al. [21] used a ductile fracture criterion based on the Zener-Hollomon parameter to predict failure in hot gas forming process. Fan et al. [22] studied the effect of hot gas forming integrated heat treatment on the Microstructure, texture and hardness of formed parts. They showed that the process must be rapid for higher formability. Wang et al. [23] studied free bulging of TA15 titanium alloy tubes by internal gas pressure at 800°C. They concluded that if the strain rate is constant during forming process, maximum of bulging ratio can be achieved. Wang et al. [24] produced metal bellows by superplastic forming. They used internal gas pressure with axial feed during forming process. Neugebauer and Schieck [25] developed a hat gas forming setup for forming high strength steel tubes with a maximum gas pressure of 80 MPa and maximum temperature of 1000°C. Liu et al. [26] investigated corner filling in hot gas forming process of titanium tubes in a square cross-sectional die. They also studied feeding effect [27] on the hot gas forming of tubes tube, which demonstrated that best temperature for higher formability is about low strength titanium alloy 800°C. Maeno et al. [28] used resistance heating system in hot gas forming process of aluminium alloy tubes. By this heating method, the temperature remained constant during forming process. Vadillo et al. [29] used numerical simulation to study the effect of loading curve in HMGF process. They could bulge Ferritic stainless steel up to 55% at 1000°C. Simulation of HMGF process was done by Rajaee et al. [30]. They obtained process window of HMGF process of AA6063 tubes using Abaqus software. Wu et al. [31] investigated forming behavior of Ti22Al24.5Nb0.5Mo rolled sheets by uniaxial tensile and hot gas bulging tests. They obtained forming limit curve under constant equivalent strain rate. Anaraki et al. [32] investigated the effect of pulsating pressure on formability in hot gas forming. Their results show that pulsating pressure can improve the thickness distribution along the tube.

So far, there are no precise investigations to predict the deformation behavior of the material using finite element method in HMGF process. Also, most of the studies are carried out on the simple shapes, such as a symmetrical bulge of the sheets and tubes. In this manuscript, the hot gas forming process of aluminum AA6063 tubes is simulated. Numerical results are compared with experimental ones which shows a good agreement. On the other hand, a hot gas forming system is designed and the experimental deformation of circular tubes into square-shaped is investigated. The effect of process parameters including forming pressure, time period of the forming process, temperature, and initial thickness of the tube on the corner radius, and thickness distribution of the final products are specified.

2. Experiments

The forming of the AA-6xxx alloy is taken into consideration due to good corrosion resistance, high strength to weight ratio, high applications in the automotive industry, and significant formability at high temperatures. Aluminum tubes with the initial external diameter of 40 mm and initial thickness of 1.5 mm is utilized. All the tubes are seamless. Initial tubes have been extruded and their mechanical properties were not changed after the extrusion process; because
heat treatment was not applied to them. The chemical composition of the tubes is determined by quantometer test, which is listed in Table 1.

According to the obtained chemical compound, the material of the tube is AA6063 alloy.

<table>
<thead>
<tr>
<th>AL</th>
<th>Mg</th>
<th>Si</th>
<th>Fe</th>
<th>Zn</th>
<th>Cu</th>
<th>Mn</th>
<th>Pb</th>
<th>Ti</th>
<th>Sn</th>
<th>Ni</th>
<th>Ga</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.47</td>
<td>0.44</td>
<td>0.30</td>
<td>0.08</td>
<td>0.06</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.017</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

2.1. Mechanical Properties Experiments (Tensile Test)

Tensile specimens were prepared using WireCut machine and then, uniaxial tests were performed using the machine, which is shown in Fig. 1 according to ASTM-E8M, in order to obtain the stress-strain diagram of the tube material.

Experiments are conducted at 25°C, 400°C, and 500°C. The strain rate ranges were chosen at three different amounts of 0.1, 0.01, and 0.001 s⁻¹ (that is, simulation results show the strain rate in this process is under 0.1s⁻¹ and the stress changes are linear). Fig. 2 shows the obtained true stress-true strain curves. The results show the fracture strain of AA6063 has increased 233% and 300% at the temperatures 400°C and 500°C, respectively, in comparison to that in room temperatures. In fact, flow stress decreases significantly as the result of softening phenomenon, and the material does not show any strain-hardening behavior at the temperatures higher than 400°C. Thus, the formability of the tube has increased and also, lower pressure is necessary to form the material. Fig. 2 (a) shows an increase in the AA6063 stress at the room temperatures by increasing the strain, due to the strain hardening. On the other hand, after the elastic deformation occurs in the higher temperatures, stress reaches a steady state. This is because of an equilibrium between work-hardening and strain-softening in high temperatures.

Fig. 1. Tensile test machine.

Fig. 2. True stress–strain curves at different temperatures; (a) 25°C; (b) 400°C; (c) 500°C.
the material property is not depended on the strain rate. Fig. 2 (b) and (c) shows the strain rate is an important parameter of the material property at the elevated temperatures, and the stress is defined according to Eq. 1.

$$\bar{\sigma} = K\bar{\varepsilon}^n \cdot \dot{\varepsilon}^m$$

Where, $\bar{\sigma}$, $\bar{\varepsilon}$, and $\dot{\varepsilon}$ are equivalent stress, equivalent strain and equivalent strain rate, respectively. $K$, $n$, and $m$ are strength coefficient, strain-hardening exponent, and strain rate.

2.2. Hot Gas Forming Setup

The hot gas forming setup (see Fig. 3) for high temperatures has been designed, in order to produce a square section tubular part with circular ends. Two types of heater were utilized to obtain the desirable temperature; (a) belt heater with a power of 1200 w which was located around the die, and (b) four cartridge elements with a power of 200 w were located in the longitudinal direction. Thus, all die parts reached the same temperature, using this combined heating system and the maximum temperature difference was observed equal to ±5 degree. The die was made from MO40 alloy steel. The hardness number of die material is 250 based on Brinell hardness test at room temperature. The die has two circular ends with the diameter of 40 mm. The square part of the die, located between two circular ends, has the square sides equal to 45 mm and the length of 100 mm in the axial direction. At the beginning, the tube was located in the square die shown in Fig. 3. The tube is fixed in its position during the process, and two metallic cones were located at the ends of the tube to achieve an appropriate sealing.

The sealing force on the metallic cones is supplied by a hydraulic press, shown in Fig. 4. Schematic image of the Sealing type is shown in Fig. 4. In the next step, the heating system raises the die and the tube temperature into the desired temperature. The temperature is measured using K-type thermocouple and is controlled by a temperature control system. After reaching the desired temperature, the internal pressure is applied by a nitrogen cylinder and controlled by a regulator, which is shown in Fig. 3. The pressure increase rate was linear in all of experiments.

3. Numerical Simulation

The process was modeled in ABAQUS 6-13 software using ABAQUS/implicit code. The aluminum tubes used were AA6063 alloy without any heat treatment. Fig. 5 shows the dimensions of the die and finite element model of the process, respectively. The die and tube are symmetrical with respect to three planes of the process configuration.
were modeled. The shell elements were used to discretize the tube, because the thickness to radius ratio of the tube was less than 0.1 [16, 17, 18]. Also, the die was modeled as a discrete rigid body. The tube was meshed using S4RT elements (four-node element using reduced integration method). The effect of element size on the simulation results was studied by considering the sizes of 3mm, 2mm, 1mm and 0.7mm.

Thickness distribution in the peripheral direction in the middle cross section of the parts, at the end of the forming process, is shown in Fig. 6 for above-mentioned element sizes. Loading condition was also maintained at the same level in four cases. There is very small variation between the results corresponding to the element sizes of 1mm and 0.7mm. Therefore, element size of 1mm was utilized in all simulations. The contact between the external surface of the tube, and the die surface was defined as a standard surface-to-surface contact, based on the Coulomb friction model. The friction coefficient between the outer surface of the tube and die was measured experimentally. Based on the experiment, friction coefficient was considered as 0.15. Material properties were obtained from uniaxial tensile tests and the true plastic stress-strain data are shown in Fig. 2. Isotropic hardening model was implemented for tube deformation in the simulations. Other properties, used in the simulation, are listed in Table 2. The simulation was performed in the form of coupled temperature-displacement analysis and all parts were assumed to have the same temperature. The gas pressure was defined with a surface uniform pressure, according to predefined path on the internal surface of the tube.

Fig. 7 (a) shows the thickness distribution of the specimen, obtained from the FE simulation of the process at 500°C and the maximum internal pressure of 12 bar. It’s obvious the minimum thickness induces in the corner of die, at the beginning part of the transitional circular-to-square zone. The experimental results also show that bursting occurs in this location (Fig. 7 (b)).

Table 2. Physical and mechanical properties of the tube.

<table>
<thead>
<tr>
<th>Parameter [unit]</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus [GPa]</td>
<td>70</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Density [kg/m3]</td>
<td>2700</td>
</tr>
<tr>
<td>Thermal conductivity [W/m°C]</td>
<td>230</td>
</tr>
<tr>
<td>Specific Heat [J/kg°C]</td>
<td>904</td>
</tr>
<tr>
<td>Expansion coefficient [m/m°C]</td>
<td>23×10-6</td>
</tr>
</tbody>
</table>
4. Results and Discussion

4.1. Validation of Simulation Results

In order to use the results of numerical simulation, it needs to verify its results with experimental data. Four different experimental tests were carried out for verification of the simulation model. Final pressure was adjusted in a way that the bursting of the tube would not occur. Formed specimens at 25°C, 400°C and 500°C are shown in Fig. 8. Formed corner radius and thickness distribution of the 1/4 middle cross section of these specimens was compared with the simulation results in the same loading condition (see Table 3).

A squared section of the specimens were cut in the peripheral direction, from the middle of the specimens to measure the wall thicknesses.

Then, wall thickness was measured by a micrometer as shown in Fig. 9(a). The changes of the wall thickness of the tubes, in experiments and numerical simulations, after processing at the temperatures of 25°C, 400°C and 500°C are shown in Fig. 9(b). The maximum differences of the thickness distribution, between simulation and experimental results, in the temperatures of 25°C, 400°C and 500°C are 2.4%, 4.55% and 5.04%, respectively. In fact, with the increasing the temperature, the error percentage for prediction of the corner radius and thickness distribution increases. Because, as the temperature increases, heat transfer of the setup to the environment increases, and so its control becomes more difficult in the experiments. Thus, the temperature distribution in the sections of the specimen becomes more non-uniform.
Fig. 9. (a) Measuring wall thickness in the middle cross section; (b) thickness distribution of specimens in simulations and experiments. Further experimentation is carried out by changing the time period of the process. That is, two specimens formed at the temperature of 500°C and bar pressure of 10, according two time periods of 30 s and 90 s (Fig. 10).

Numerical simulations were conducted with the same conditions as experiments and the obtained radii were compared. Table 4 compares the experimental and numerical results. Results show the finite element method could be used for the prediction of the deformation in HMGF of AA6063 tubes.

### Table 3. Numerical and Experimental result comparison.

<table>
<thead>
<tr>
<th>Process temperature</th>
<th>Gas pressure</th>
<th>Radius (simulation) [mm]</th>
<th>Radius (experiment) [mm]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>157</td>
<td>19.98</td>
<td>19.4</td>
<td>3</td>
</tr>
<tr>
<td>400</td>
<td>20</td>
<td>6.81</td>
<td>6.5</td>
<td>4.76</td>
</tr>
<tr>
<td>500</td>
<td>12</td>
<td>6.01</td>
<td>5.7</td>
<td>5.44</td>
</tr>
</tbody>
</table>

### Table 4. Numerical and Experimental result comparison for different time periods.

<table>
<thead>
<tr>
<th>Process temperature</th>
<th>Gas pressure</th>
<th>Process time [s]</th>
<th>Radius (simulation) [mm]</th>
<th>Radius (experiment) [mm]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>10</td>
<td>30</td>
<td>7.97</td>
<td>7.6</td>
<td>4.86</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>90</td>
<td>7.3</td>
<td>7</td>
<td>4.28</td>
</tr>
</tbody>
</table>

Fig. 10. Specimens produced at different time period of process; (a) 30 s; (b) 90 s.

4.2. Effect of Process Temperature on the Pressure

The results of the uniaxial tensile test show that with increasing temperature from 25°C to 500°C, yield stress reduces significantly. Therefore, the required deformation force of the process decreases and the final shape could be formed by a lower gas pressure. The minimum required pressure for obtaining the minimum corner radius in the tubes (without bursting) at three different temperatures of 25°C, 400°C and 500°C are illustrated in Fig. 11. It shows the increasing process temperature from 25°C to 400°C and 500°C, decreases the required internal pressure of the gas in the factor of 87.2 % and 92.3% respectively. In fact, the internal pressure required to achieve the corner radius of 19.4 mm at 25°C is equal to 157 bar, while at temperatures of 400°C and 500°C (for producing corner radius of 6.5 mm and 5.7 mm) the required pressure reduces to 20 bar and 12 bar, respectively. This leads to the possibility of using a lower capacity press machine to seal the tube ends, reducing the clamping force of the die, and as a consequence, reducing the cost of dies and components. In addition, internal pressure can be provided by simpler procedures; hydraulic pumps are utilized to supply the high forming pressures in the Hydroforming process, while the gas cylinder is sufficient in HMGF process. Also, lower applied forming pressure
makes this process as a more safe process, compared to other processes.

4.3. Effect of Process Temperature on the Formed Radius

The corner radius of the square parts is one of the significant outputs of the process. As the radius corner decreases, it means the specimen has a more detailed square-shaped. The results depict with increasing the process temperature, the fracture strain increases, flow stress decreases and the effect of work-hardening decreases as well, thus, a smaller corner radius achieves. Fig. 12 shows the corner radius at the ambient temperature is equal to 19.98 mm, while HMGF at the temperatures of 400°C and 500°C, reduces the corner radius of the products 66.48% and 69.91%, respectively.

4.4. Effect of Temperature on the Thickness Distribution

Thickness of the final products is considered as a geometrical criteria, which indicates the quality of the products. Fig. 13 illustrates the thickness changes of the tube cross section, in the middle of the specimen, at three temperatures of 25°C, 400°C and 500°C. As it’s shown, the thinning is low and the thickness distribution is more uniform at ambient temperatures, due to a low plastic deformation in the specimen. The minimum thickness of the tube wall is 1.29 mm. On the other hand, when the temperature reaches to 400°C and 500°C, the values of deformation enhances and the square corners experiences a more deformation. In fact, the material flows from the points (which are in contact with the die) to the corners. Because of the lack of axial feeding, the thickness reduces significantly and the minimum thickness reaches to 1.14 mm, and 1.04 mm at 400°C and 500°C, respectively. Also, the minimum thickness occurs in the transition zone (Fig. 13). Transition zone is a part of the tube wall, in which the tube loses its contact with the die surface.

The results show the mechanical behavior of AA6063 alloy is similar to superplastic materials as the temperature increases. Thus, complex shapes and small-radius corners could be produced at the elevated temperatures.

Fig. 11. Required forming pressure in different temperatures.

Fig. 12. Effect of process temperature on the formed corner radius.

Fig. 13. Thickness distribution in different temperatures.

Fig. 14 illustrates the changes of the thickness in middle cross section of the tube, during the process at 500°C and a pressure of 12 bar. First, the thickness of the specimen decreases uniformly and the tube bulges freely. In this step, the specimen has not any contact with the die and there is no friction between specimen and die. By
increasing internal pressure, the specimen deforms more and therefore, contacts with the die surfaces. Thickness starts to change non-uniformly (i.e. from the pressure of 5.8 bar); when the specimen touches the die due to the friction between tube wall and die surface. Thus, the material flows hardly where the specimen has a contact with die, and the thickness does not change very much, because of the existing friction between the die and external surface of the tube. Consequently, final thickness of the specimen in these areas is much greater than the other. On the other hand, the area without any contact with the die expands freely and becomes thin. This area needs to be fed from the part of the tube, which has a contact with the die. However, the material in the contact zone has a difficult flow to the free expanding parts, due to the friction. As a result, the free expanding zone becomes thinner, compared to the parts which have a contact with the die. The transition zone (i.e. the boundary between the expanding area and the area that has a contact with the die) is under the effect of two opposite direction forces; (1) the forming force applied to this area because of the expansion; and (2) the friction force applied in an opposite direction, which inhibits the material from flowing. The interaction between these two forces induces more tensile stress rather than other parts in the peripheral direction of the transition zone.

Fig. 14. Changing of the thickness distribution during the process.

Fig. 15 shows stress and thickness distribution in the peripheral direction when a temperature of 500°C and a pressure of 12 bar is applied to the tube. Since, the values of stress in the transition zone is greater than other area, the zone reaches the ultimate stress sooner, and becomes thinner than other area.

Fig. 15. Stress and thickness distribution in the middle of final specimen.

4.5. Effect of Time Period of the Process

When the time period of the forming increases, the rate of internal pressurizing of the gas decreases. Thus, the deformation rate and as a consequence the strain rate, which effects on the flow stress of the material decreases. In the condition of decreasing strain rate and high temperatures applied to AA6063 tubes, the value of fracture strain increases and the material enables to be formed more. Numerical simulations at a temperature of 500°C and a pressure of 10 bar and different time periods were carried out. The results shown in Fig. 16 depict with an increase in the time period of the process from 30 s to 90 s, the formability of the material increases and the corner radius decreases in the factor of 8.4%.
4.6 Effects of the Loading Path

4.6.1. Constant Pressure in the End of Process

When the process is performed with a constant pressure at room temperatures, the amount of the corner radius does not change. Because of the hard-working phenomenon, the yield stress increases, and thus, higher pressures are required to form the tube more. Recall that for AA6063 at elevated temperatures of 400°C and 500°C, the effect of hard-working assumed to be negligible and the strain increases when the stress is applied in a constant magnitude (see Fig. 2). In addition, stress is a function of strain rate at high temperatures, and strain rate reduces after a little plastic deformation occurs (i.e. stress reaches its maximum and becomes constant). As shown in Fig. 2, decreasing the strain rate reduces the yield stress of the material.

The changes of the corner radius during the process is illustrated in Fig. 17. In the first step of the process, the pressure reaches its maximum value within 20 s, and in the second step, it becomes steady up to the end of the process. In the first step, radius increases slowly during the initial elastic deformation. However, the changes of the corner radius increases rapidly during consequence plastic deformation. The radius increases with a constant rate and the specimen expands uniformly until it touches the die. Then, the radius amount starts to reduce (i.e. when the pressure reached its highest value of 12 bar, the corner radius was 7.17 mm). In the second stage, the changes of the corner radius become lower when the time passes, and reaches 5.99 mm within 80 s in the constant pressure of 12 bar (that is, corner radius reduces 16.5% during the second step).

4.6.2. Different Loading Paths

Loading path is one of the effective parameters in the HMGF process. For investigating the effect of this parameter on the formability of the material, different loading paths were applied at a temperature of 500°C and a pressure of 12 bar (Fig. 18). Also, the changes of the corner radius during the forming process regarding to different loading paths is shown in Fig. 19. As it’s shown, the maximum deformation and minimum corner radius belongs to the loading path #2 (the corner radius formed is 5.47 mm). In addition, the maximum value of the corner radius is 6.3 mm and belongs to the loading path #4.

Fig. 17. Changes of corner radius during process.

Fig. 16. Effect of time period of forming process on formed radius.
a point which has the lowest amount of thickness). For the loading path #2, pressure was applied with the largest rate and therefore, strain rate is high (Fig. 20). Thus, the tube bulges freely and the thinning of the tube occurs uniformly along the perimeter of the tube. Considering the fixed process time (i.e. 30 s), the shorter the time of free bulging, the more time to form the tube corners at the second part of the loading path. As shown in Fig. 20, when the corners are formed, the lowest amount of strain rate appears in loading path #2, due to having a more time in this step. Moreover, the fracture strain increases with decreasing the strain rate. As a consequence, the tube forms more and corner radius becomes smaller. Loading path #1, in which the pressure increases with a constant slope, has a higher strain rate, and because the fracture strain decreases, consequent corner radius is less than that of in loading path #2. Finally, in loading path #3 and #4, there is a constant pressure section during the process. When the pressure is constant, strain increases with a lower slope therefore, low amount of the deformation occurs. Moreover, in other times when the pressure is not constant, it increases with higher slope. Consequently, with increasing strain rate ultimate strain increases.
5. Conclusion

In this paper, aluminum AA6063 tubes with square cross section were produced, using hot gas forming process. Different loading conditions were studied at elevated temperatures to obtain the maximum value of formality and minimum corner radius, as well. The results show that with increasing the temperature the formability of the material increases and lower corner radius is formed. In fact, the thinning in the transition zone is maximized and it limits formability. By increasing the process time period, the strain rate becomes smaller and lower corner radiuses could be obtained. At the elevated temperatures, the forming process of the tube continues in a constant pressure, because of the superplastic behavior of the material. Also, lower amount of corner radius is achieved. By increasing the time of loading, it is possible to decrease the corner radius by the factor of 8.4 % at 500°C. Furthermore, it is observed the maximum amount of forming could be obtained, if the internal pressurizing rate of the process increases at the initial step (i.e. during the bulging of the tube). In the next step (when the corner radius is to be formed), the rate of gas pressurizing should be decreased.

References


