Journal of Mechanics Engineering and Automation 8 (2018) 60-70
doi: 10.17265/2159-5275/2018.02.003

Optimizing Hot Forging Process Parameters of Hollow Parts Using Tubular and Cylindrical Workpiece: Numerical Analysis and Experimental Validation

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Abstract: CAE (computer aided engineering) evaluates the forging process virtually to optimize the industrial production. The numerical and experimental investigations of forging process of a hollow part are important in industrial point of view. This study has been focused on the development of a 3D elastic-plastic FEM (finite element model) of hot forging to evaluate the forming process of hollow parts. The validity of this method was verified through a laboratory experiment using aluminum alloy (AA6351) with medium geometric complexity. The distributions of effective strain, temperature, metal flow and strength were analyzed for two different initial workpieces (tubular and cylindrical). It was observed that both initial workpieces can be used to produce the final hollow part using the numerical simulation model. The results showed that the numerical analyses predict, filling cavity, calculated strength, work temperature and material flow were in agreement with the experimental results. However, some problems such as air trapping in the die causing incomplete filling could not be predicted and this problem was resolved experimentally by drilling small holes for air release in the dies.

Key words: Hot forging, FEM, hollow parts, AA6351.

1. Introduction

Economically, forged products are attractive due to superior strength when subjected to mechanical stresses, the micro-structural homogeneity achieved and the greater ease with which the forgings can be post-processed by automated methods [1]. The largest consumer of forged products is the automotive industry, with an annual requirement of 58% of all world production. Recent data show that the world's largest producers of vehicles are China, the United States, Japan, Germany, South Korea, India, Mexico and Brazil, respectively in descending order of production [2]. In 2014, the world produced 89.5 million cars in 2015, 91 million, and by 2020, the goal is to reach 100 million cars per year [3].

The flanges are used for components such as pipes for suspension, steering and transmission systems, among others [4]. Manufacturing of flanges by means of metal forming processes is the subject of many scientific works. Among technologies permitting flanges forming there are the methods for full and hollow parts and for obtaining cylindrical and shaped flanges [5]. However, when a hollow part is being forged, a machining operation is necessary to make a central hole, for instance, in this case, machining can be eliminated if the forging process is performed from a hollow workpiece instead a massive workpiece. The hollow workpiece reduces the raw material and energy in the forging process, which can be very significant depending on the weight, geometry, material and batch size of the part.

The feasibility of manufacturing parts while saving

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raw material and getting a high-quality product makes hot forging with tubular workpieces a good alternative, mainly in the cases that long machining processes after forging are required [6]. Through numerical simulation, it is possible to find process routs for reducing the manufacturing time and consequently, the cost [7].

In recent years, the mechanical forming industry has been experiencing a major advance in the design area due to the improvement of the numerical simulation programs of this process [8, 9]. In the mid-1990s, most programs enabled the simulation of the forging process for pieces with axial symmetry and others, in which the flow of material could be approximated as occurring in only two dimensions [10]. Nowadays, it can be said that simulation programs have become an essential method for the development and optimization of the metal forming process. Numerous commercial programs, based on different solution methods, are available in the market [11, 12].

Within this context, the developed 3D elastic-plastic FEM (finite element model) was used to analyze a hot closed die forging process to obtain an axial part that was used to join components in the automotive industry using two different workpiece geometries (tubular and cylindrical). Beyond verifying the feasibility, it will be also analyzed for possible improvements in the process and the optimization of the process. The main objective for the use of two different geometries is obtaining the part with minimum raw material and eliminating experimental work that would be necessary without a previous simulation.

2. Material Data

The material used to make the workpieces was a commercially available AA6351 aluminum alloy. The chemical components of AA6351 are listed in Table 1.

It was showed in flow curves determined experimentally that not only strain but also strain rate and temperature have a great influence on the flow properties of AA6351 [13]. According to Fig. 1, the flow stress increases as the temperature decreases and the strain rate increases.

However, to facilitate insertion of material flow curves into numerical simulation software is necessary that they can be represented by a mathematical equation, considering the model of Hansel-Spittel, in Eq. (1). Table 2 gives the values of the optimized Hansel-Spittel parameter.

$$\sigma = \sigma_0 . e^{-m1T} . \varepsilon^{m2} . \dot{\varepsilon}^{m3} \quad (1)$$

The mechanical and thermal properties of the AA6351 aluminum alloy material are listed in Table 3.

Table 1 Chemical components of AA6351.

Al	Si	Fe	Mg	Mn	Ti	Zn	Cu
97.07	0.42	0.29	0.82	0.24	0.013	0.01	0.18

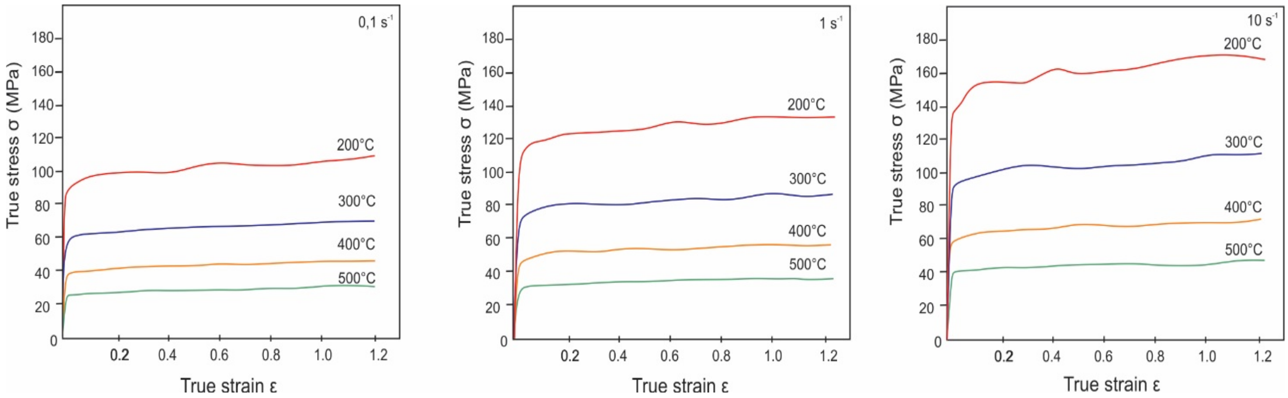

Fig. 1 The temperature and strain rate dependence of flow curve for AA6351.

Table 2 Optimized parameters of the Hansel-Spittel model [12].

Parameters	Hansel-Spittel
σ_0 (MPa)	303.5
m_1	-0.0043
m_2	0.103
m_3	0.057
T (°C)	400

Table 3 Mechanical and thermal properties of the AA6351.

Parameters	Values
Density (kg/m^3)	2,600
Poisson'sratio	0.33
Young modulus (GPa)	70-80 (T dependent)
Specific heat (J/(g-K))	0.89
Thermal conductivity (W/(m-K))	176
Heat transfer coefficient (blank-tools) (W/(m^{2}K))	12.5 (150 MPa)

Table 4 Mechanical and thermal properties of the H13.

Parameters	Values
Density (kg/m^3)	7,690
Poisson'sratio	0.33
Young modulus (GPa)	210 (T dependent)
Specific heat (J/(g-K))	0.460
Thermal conductivity (W/(m-K))	24.7

The commercially available H13 tool steel was used to make the dies. The mechanical and thermal properties of the H13 material are listed in Table 4.

3. Numerical Modeling

The geometry of the final part is shown in Fig. 2. It was obtained through the 3D modeling of the part developed in the SolidWorks® software. The use of this system allowed a series of automations with regard to the modeling of the part, workpieces and dies.

Fig. 3 shows the main dimensions (mm) of the study part. The walls of the piece were designed with angle of 7. A higher angle was chosen to avoid the probability of adhesion of the piece to the tool.

The dimensions of the tube were: height of 35.5 mm, width of 41.5 mm and concentric hole of 12 mm in diameter. The dimensions of the cylindrical workpiece were: height of 32 mm and width of 41.5 mm. It was possible to estimate the dimensions of the initial workpiece by the volume conservation law, considering the volumes of the final part, the flash and the flash land.

The designs of the flash land and the parting line were required to develop the dies project. Fig. 4 shows a cross-sectional view of the upper and lower dies, the air out channel, the guide pin and a simulated piece representation.

The software Simufact® was used to evaluate the die filling and the manufacturing of parts within dimensional tolerances. Furthermore, the parameters that were involved in the process were also analyzed, such as the workpiece and die geometry, forging strength, temperature and friction. The finite element method was chosen to analyze the forging process. Due to the geometry of the part, a 3D simulation was used, the results of which are more reliable and fit better to the hot forging process. These considerations are indicated in the literature by the software manufacturer and others studies [8].

The introduction of the method that was used is defined at the beginning of the work. Furthermore, in

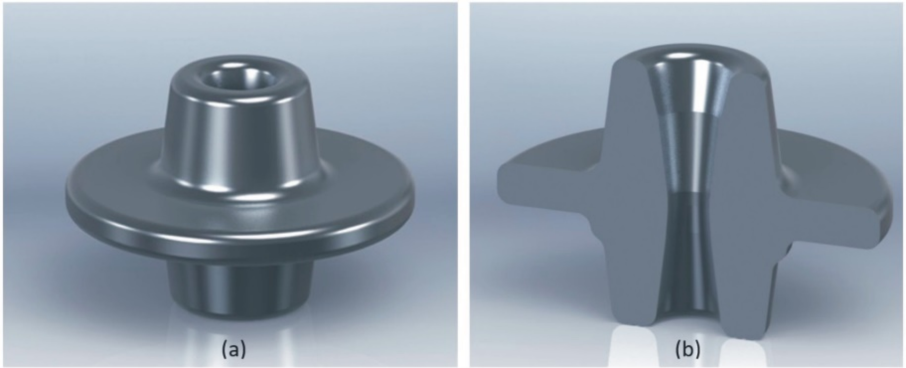

Fig. 2 (a) The 3D representation of the part to be forged; and (b) Cross-sectional view.

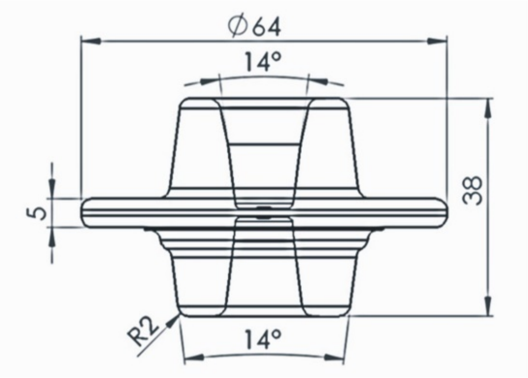

Fig. 3 The main dimensions of the final part.

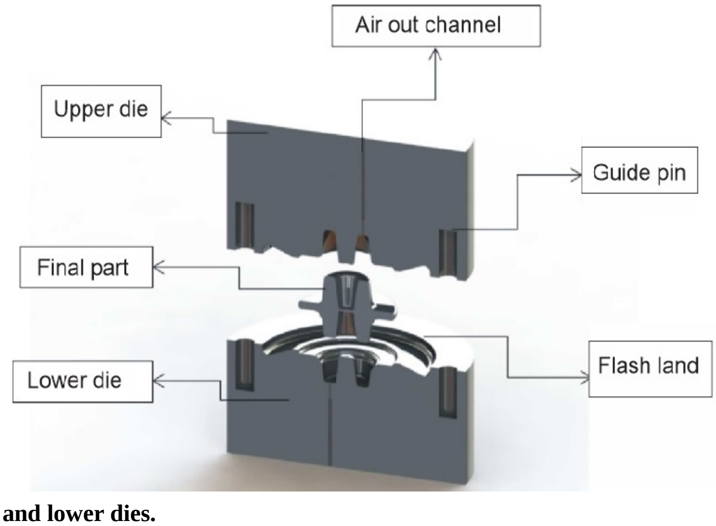

Fig. 4 Design of the upper and lower dies.

this stage, the type of process is defined, for example, if it would be a hot or cold forging process, and the number of dies which would be used in the simulation.

The thermal and mechanical properties of the AA6351 and H13 aluminum alloy are described in Tables 3 and 4 and these were inserted into the Simufact Software database. The true stress-strain curves of the AA6351 at various temperatures are input into the preprocessor of Simufact. Forming in the form of table, showed in Table 1. The material of the workpieces is defined as a homogeneous and isotropic elastic-plastic body. The tools are considered to be rigid but non-isothermal.

Friction and contact heat conduction exist at the interfaces between the blank and the tools. Hence, the Coulomb friction model is employed, and the friction coefficients are assumed to be constant during analysis.

The mesh size, type and number of elements will be informed by the software, and the data influence directly on the results presented by the simulation [8]. The simulations were performed with two types of mesh, 2D and 3D, and it was determined that the best mesh to be used is 3D, since it had satisfactory results. Thus, a mesh of 1 mm was used, the type of element was hexahedral and the number of elements created was 15.484. Fig. 5 shows this mesh.

The parameters of the process used in the simulation are very important for reliable results and are shown in Fig. 6.

4. Experimental Forging Process

The same parameters of the simulation were used in order to compare the results obtained in the numerical simulation and the experiments performed. The hydraulic press with capacity of 6.000 kN and tool velocity of 3.4 mm/s was used in the experimental process. The parameter configurations for the operation of the hydraulic press were done through a system called Siemens HMI. This interface system allows one to set all the parameters of the hydraulic press and change them, if it is necessary. The dies were connected to the press with appropriate clamps to avoid the occurrence of relative movements between the dies during the forging process. The tools had guide pins to prevent shifting during the process. They were heated by conduction temperature to 300 °C.

The workpieces were heated to a temperature of 400 °C in an electric furnace. In the process sequence, these workpieces were dipped in synthetic lubricant solution in order to obtain a lubricating film surrounding them. The dies were sprayed with the same synthetic lubricant solution to obtain a better lubricating surface.

5. Results and Discussion

5.1 Numerical Analysis

In the first attempt to fill of the cavity, it was observed that with the initial volume of the workpieces, it was not possible to obtain the complete filling. Thus, observing the law of constant volume the geometry was changed until complete filling of the cavity was possible, as shown in Fig. 7.

After changing the dimensions of the workpiece, the computer numerical simulation did not show any incompletely filled points, indicating that the entire surface of the dies cavity was in contact with the metal material.

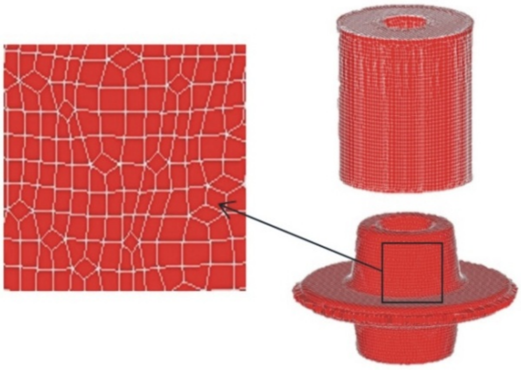

Fig. 5 The design of the mesh and the created workpiece.

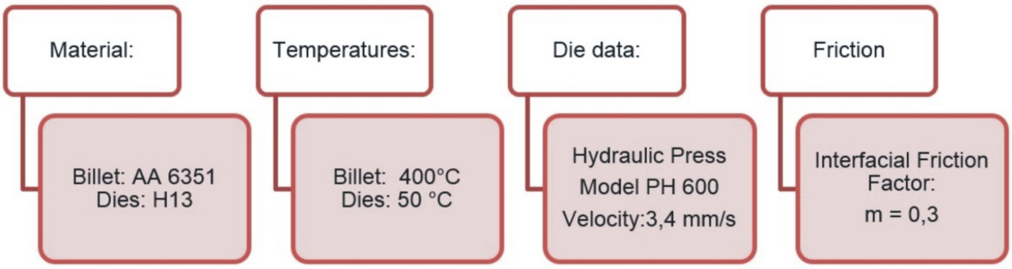

Fig. 6 The input parameters of the process inserted into the simulation program.

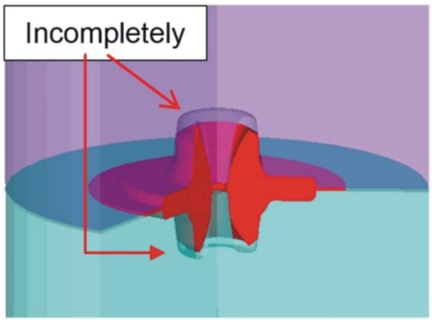

Fig. 7 The die incompletely filling.

With regard to the process temperature and its evolution during the imposed deformation, it was observed that the region next to the metal flash channel is the one that holds the highest temperature. This high temperature occurred in the metal flash channel because of the greater deformation and friction during the process. In addition, it is the last part that came into contact with the die. Fig. 8 shows the distribution of the temperatures reached at the end of the forging process.

Fig. 8 shows that the lowest temperature was located at the top and bottom of the part. The average temperature in these regions remained constant around 50 °C. Furthermore, these regions presented rapid cooling rates because of the smaller thickness and large area with contact to the die. It was also observed that the highest temperature occurred in the input of the flash lands, and it was 70 °C in average.

The deformation was carried out in a single and continuous molding step. The regions that were represented by the red color in the Simufact® software are those that presented greater deformation in the forging process, as shown in Fig. 9.

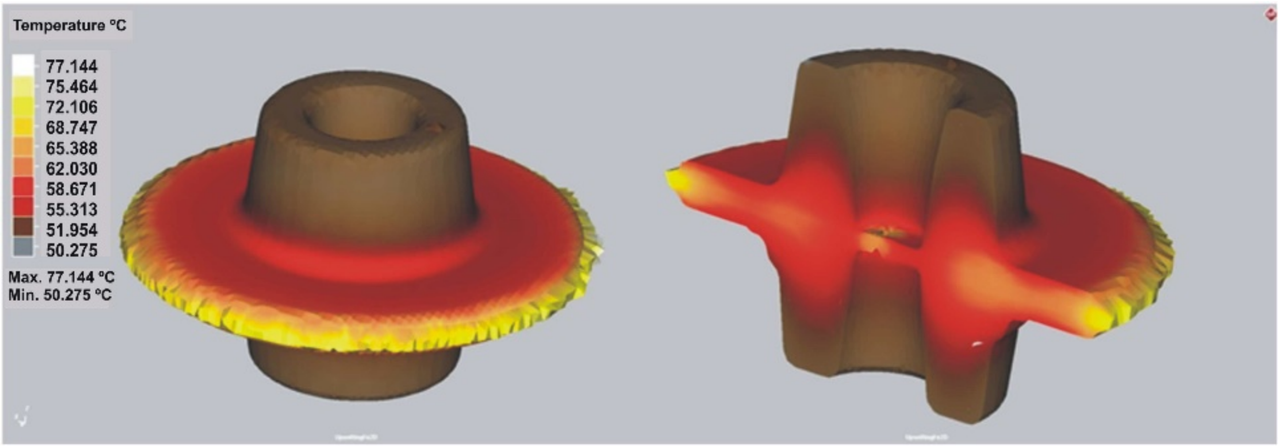

Fig. 8 The distribution of the temperatures reached at the end of the forging process.

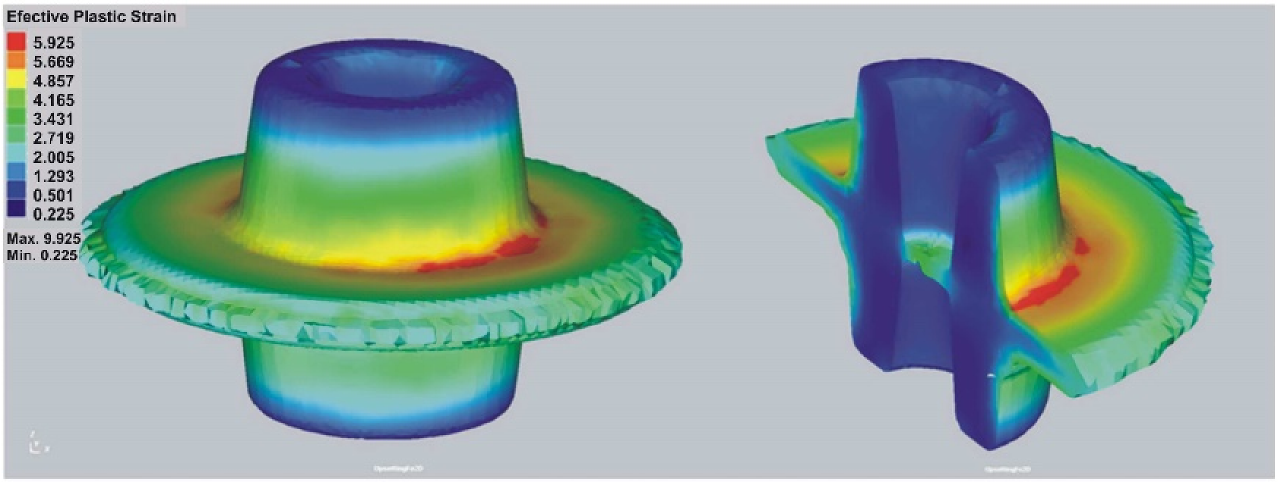

Fig. 9 Plastic deformation.

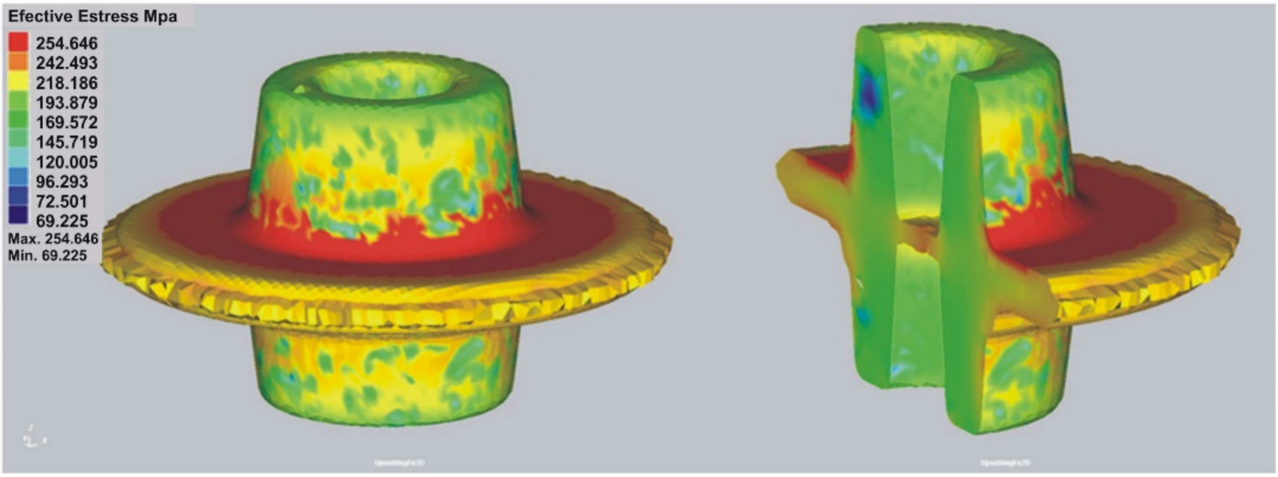

Fig. 10 The tension distribution.

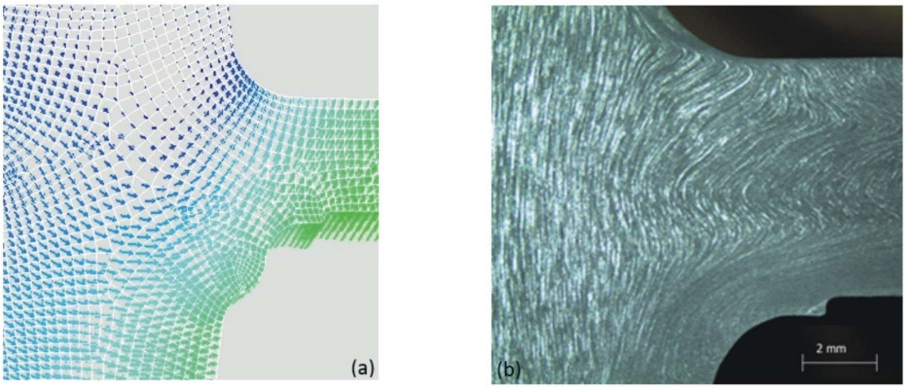

Fig. 11 (a) The flow lines in the material obtained in the simulation of the forging process; and (b) Shows the real flow lines during the forging process through a macrograph analysis.

Fig. 9 shows that the deformation presented a heterogeneous distribution in the section of the metal bar. It was also observed in the region which presented the highest concentration of tension, where the material experienced the highest deformation. The cause of this is because the material was forced to change its flow direction, shown in Fig. 10.

Fig. 11a shows the flow lines in the material obtained in the simulation of the forging process and Fig. 11b shows the real flow lines during the forging process through a macrograph analysis. In this simulation image versus the real macrograph image, it is observed that the flow lines during the forging process are similar.

The numerical simulation of the both workpiece showed similar results for plastic deformation, tension distribution and cooling. It was presented previously the result to simulation using the tubular workpiece. This phenomenon may be attributed to the same process parameters used in the simulation for the both geometries.

However, in relation to the forging force, two processing results are showed, all of them considering a single step deformation. The force required for the forging of the tubular workpiece, obtained in the numerical computational simulation was 2,432.05 kN.

The strength required for the forging of the cylindrical workpiece piece was 2,814.51 kN. It is possible to observe that at the beginning, the strength rose abruptly, when the material was forced to flow to the side of the piece. This occurred differently from the tubular workpiece, in which the strength rose steadily and increased more significantly at the end of the process, during the filling of the metal flash channel. It may be attributed to the different material flow inside die cavities. The tubular workpiece geometry facilitated the flow of the material into the upper and lower regions of the dies due to the volume distribution around the inner pins.

5.2 Experimental Analysis

In order to verify the numerical modeling guess the part of the forging obtained from the experimental forging process was compared with that of the numerical model obtained from the simulation.

The first difficulty during the forging process was not predicted by the simulation. It was to correctly position the both of workpieces on the die. For the material to flow evenly, it is necessary to center the workpiece in the die at the beginning of the process. As a result, the material flowed unevenly into the cavity, causing deformation in the central pin of the die. Fig. 12 shows an example of these problems.

In addition, the parts manufactured in the first experiment did not completely fill the cavity of the die, as shown in Fig. 13. This problem occurred mainly due to the release of the trapped air in the cavity of the dies. It also was not predicted by the simulation.

For the forging process, the cylindrical workpiece must be larger. This workpiece was larger than what was calculated using the Volume Constancy Law. This was required because the material exhibits resistance to flow in the direction of filling of the upper die, flowing more easily into the metal flash land channel. It was predicted by the numerical simulation, first the new geometry was simulated and then experimented.

The problems that occurred during the first test were corrected for the second forging process. To facilitate the positioning of the workpiece in the die, it was inserted 0.5 mm lower. As a result of this repositioning, the workpiece remained in the same position such as simulated. To facilitate the exit of air released by the material during heating, a hole with a diameter of 1 mm was inserted in each of the dies, as shown in Fig. 14.

Fig. 15 shows the forged parts, obtained from the tubular and cylindrical workpieces. After the visual analysis of both pieces, it was concluded that it is possible to manufacture them free of defects.

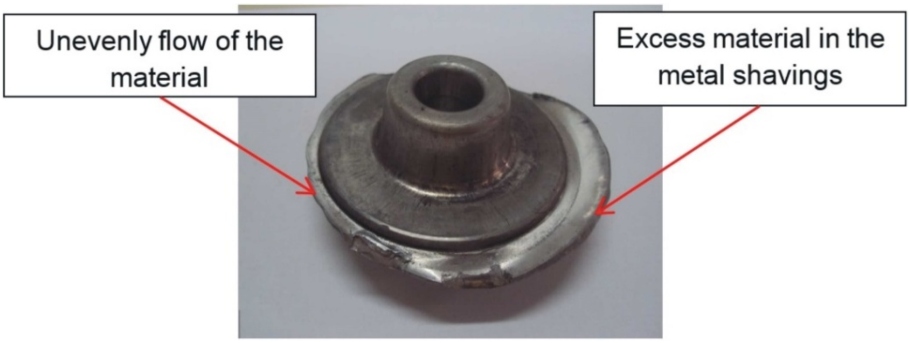

Fig. 12 First experiment: unevenly distributed of the material.

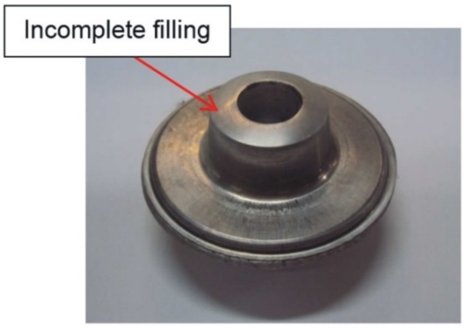

Fig. 13 First test: incomplete filling.

Fig. 14 The holes to facilitate the exit of air.

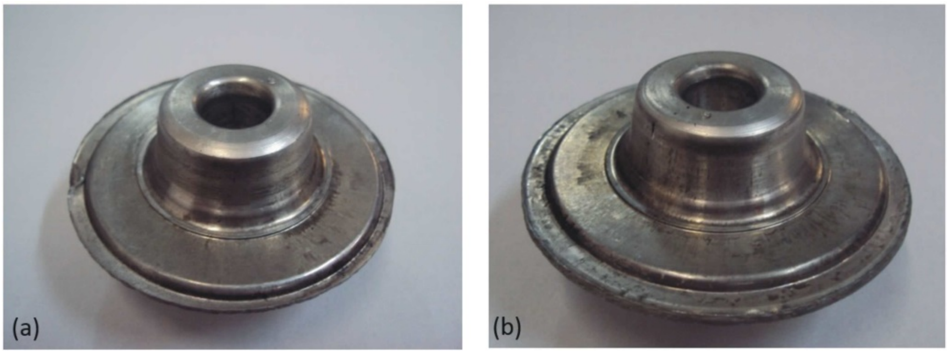

Fig. 15 Forged parts: (a) Tubular workpiece; and (b) Cylindrical workpiece.

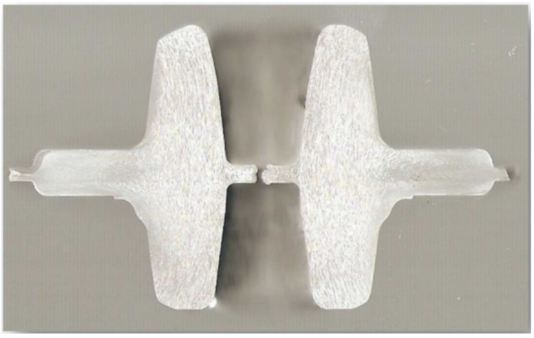

Fig. 16 Macrography.

After cutting the piece and polishing it, a reagent called Aqua Regia was applied over the section under study, with the aid of a cotton swab. Fig. 16 shows the macrostructure, where the flow lines that formed during the forging process can be observed.

The experimental flow lines and the predicted by simulation are equivalent and prove how the material is forming in direction to all parts to cavities and flash land.

In the experimental forging process, the total strength measured by the load cell was approximately 3,432 kN for the cylindrical workpiece, and 2,451 kN for the hollow workpiece, as shown in Figs. 18 and 19.

The graphs shown in Figs. 17 and 18 indicate that during the forging process of the material, a higher strength occurred mainly at the finish of filling the cavity. The strength values increased when details of the geometry were filling and the material flow to the flash land reaches the maximum value when the dies were complete closed. Furthermore, the temperature decrease happened due to the contact with the dies also contributing to increase strength. It was also observed that it is hard to fill in the thinnest parts of the piece.

In the analysis of Fig. 19, differences between the strength values obtained by the experiment vs. the simulation were observed. The simulation obtained a lower percentage of difference in the maximum strength, for the tubular workpiece in regard to the experimental one. This difference occurs mainly due to the real processing conditions and those input in the software.

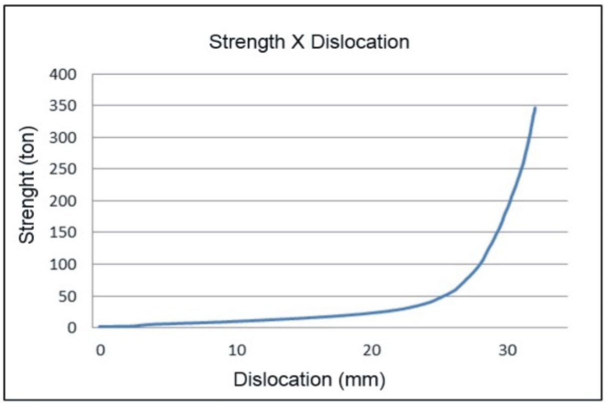

Fig. 17 The strength versus dislocation graph obtained from the experiment using a cylindrical workpiece.

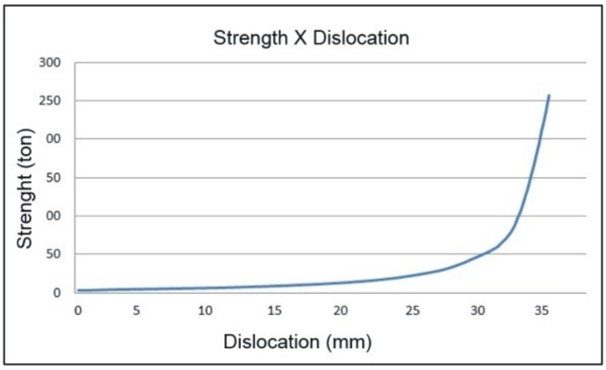

Fig. 18 The strength versus dislocation graph obtained from the experiment using a tubular workpiece.

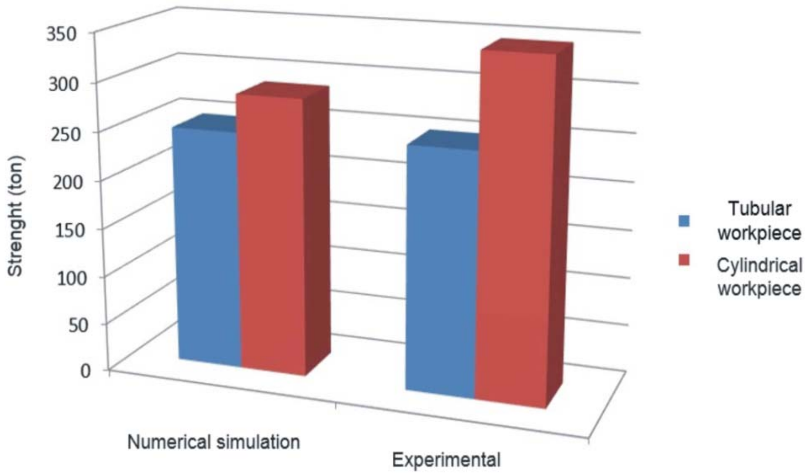

Fig. 19 The simulated and experimental strength.

The forging process of the cylindrical workpiece presented simulated and experimental higher strength. The difference between strength value in experimental and simulated also can be attributed to processing conditions such as the transfer of workpiece from oven to press, cooling, time to workpiece position, and the difficult to a massive workpiece (cylindrical) material flow to flash land cavity.

6. Conclusions

The forging method used for optimization of hollow parts was proposed; FE simulation and forging experiment results confirmed feasibility of using tubular workpieces.

The FE simulation could not predict the air trapping in the dies and workpiece position, and these issues were identified during the experimental test. These problems were overcome with the insertion of output air channels in the upper and lower dies. In addition, a hole with a diameter of 1 mm was inserted in each of the dies to improve the positioning of the workpieces.

When the forged parts were compared with the simulated ones, the results presented by the numerical simulation were similar and can be used for the development of forging processes as an aid to reduce time and costs of the development of new processes.

The results obtained by the FE simulation and experiments indicated only trifling differences in strength results. Thus, the developed FE simulation model can be used to successfully predict the strength required to forge.

The behavior of the material during the metal forming can also be estimated using the FE simulation. The results of experimental and simulation were similar.

Through visual and macrograph analysis of the pieces, it was concluded that it is possible to manufacture hollow parts free from failures and surface defects using a hollow workpiece.

Finally, the FEM method is an efficient tool to plan the forging process, but difference on results occurs mainly due to the real processing conditions. Improving FEM method to approach for the real processing conditions is a challenge to the simulations programs.

Acknowledgements

The authors thank the Laboratory of Mechanical Transformation (LdTM), the Federal University of Rio Grande do Sul (UFRGS), and the financial support institutions CNPq (National Council for Scientific and Technological Development) and CAPES (Coordination for the Improvement of Higher Education Personnel).

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