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NUMERICAL SIMULATION OF MULTI-DIRECTIONAL HOT FORGING FOR THE REDUCTION OF FORGING DEFECTS

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Abstract. Hot forging is a metal forming process widely used in the industry. Among the many advantages are the possibility of severe plastic deformation and the improvement of mechanical properties, leading to the continued development of forging for industrial applications. The conventional hot forging of complex geometry components is performed in several steps, what is favorable to initiate, or propagate defects formed in the early steps due to the deformation path. In order to obtain products in a single processing step, this research aimed the development of an innovative multi-directional forging process. The finite element method was used to simulate the manufacturing of a 38MnSiVS5 steel connecting rod to preview the distributions of temperature, equivalent strain and von Mises stress in the forged product, as well as the formation of defects. Billets with the same volume and different lengths and widths were simulated to achieve the best material flow, which avoids fold and other forging defects, and leads to the complete flashless filling of the die. The simulation results made possible to know the proper billet geometry and the best friction condition for the proposed process.

1 INTRODUCTION

Many automobile components for engines are produced by forging because it provides high mechanical properties as result of the suitable compressive stresses due to power hammers or presses. The main goal of the forging industries is to improve manufacturing processes to reduce raw material costs, which are a major component of the product cost, to avoid defects and get higher quality products. Excess of material usually is necessary in conventional forging to guarantee the filling of the die cavity, which results in flash around the part. Thus, industry attention shifts to the proper development of production technologies, by developing quick and cheap processes and improving dies and tools to satisfy these requirements.

Therefore, many researches have been developed in order to improve hot forging. Vazquez and Altan [1] proposed the preform design for flashless forging of a connecting rod and introduced a new tooling concept for forging of complex parts with a controlled amount of flash. Zhao et al. [2] studied the die cavity design of near flashless process using FEM-based backward simulation to reduce the material lost as flash by the design of an improved busting operation for a track link forging. Behrens et al. [3] developed a precision forging processes for high-duty automotive components, exemplarily for helical gearwheel and a crankshaft, consisting of multistage processes seeking to achieve high quality parts and dimensional accuracy. Behrens et al. [4] also proved that is possible to produce a two-cylinder-crankshaft without flash using a multi-directional forging as a stage of process and with a method to compensate the shrinking of the part. Grosman et al. [5] developed a deformation process that is strictly based on small incremental deformations realized by a series of thin anvils. According to the authors, this manufacturing technology enables large plastic deformations during cold forming without the need of additional heat treatment operations, reduces the applied loads and the total energy required to obtain an appropriate level of accumulated equivalent strain, besides of obtaining an unusual set of properties in the final product.

In this research, it is proposed a novel multi-directional precision forging of connecting rods aiming to obtain geometric features without the need of so many manufacturing steps, and to achieve the best results in terms of material flow, dies filling and forging defects.

Thus, the main advantage of multidirectional forging is to obtain products with geometric features that are normally not possible in conventional forging, without the need of excessive loads, or many forging steps as in the conventional process. With this technology, the part can be formed in many directions, in one single step. This allows a greater degree of deformation and a reduction in total process time, and makes possible a better control of material flow [6].

Forging depends on many factors as workpiece temperature, friction, die shape, as well as billet geometry. The difficulty in controlling all these factors tends to cause defects in the part. Thottungal and Sijo [7] pointed out the various forging defects that occur in a forging industry that cause the rejection of the part. The defects in the forged components include the lapping, mismatch, scale, underfilling, quench cracks, among others.

Some studies have been carried out on the forming quality in the forged part to prevent defect, which can reduce the cost of the production. Petrov et al. [8] studied the prevention of lap formation in near net shape isothermal forging technology of part of irregular shape seeking to obtain a forged part without any defect by one press strike instead of technology concerning two forging operations. Song and Im [9] investigated the influence of forming method, punch location and billet diameter on material flow behavior and forming of bevel gear by finite element analysis with the objective to avoid underfilling and folding defect. Chan et al. [10] proposed a dynamic change in the tooling geometry to control the flow-induced defects, such as folding. Abdullah et al. [11] investigated the effect of punch geometry and location of the pin head on defect formation to ensure the accurate assembly of the blade to the hubs. Recently, Lee et al. [12] have analyzed the shape optimization of the workpiece in the forging process using equivalent static load. Gao et al. [13] have developed a prediction model for the folding defect in transitional region during local loading forming of rib-web component by the combination of finite element simulation, space-filling Maximin Latin hypercube designs method and back-propagation neural network.

Behrens et al. [6] have analyzed the boundary conditions for multi-directional forging. They showed that for a given tool geometry, multi-directional forging permits the realization of fold-free forgings. This paper aimed the development of multi-directional to produce connecting rod made with microalloyed steel, and investigate the influence of billet geometry in forging defect formation. The FE model of process was established based on FORGE 2008. The FE model was utilized to analyze the forming quality for different billet dimensions and to preview the distributions of temperature, equivalent strain and von Mises stress in the forged product, as well as the formation of internal defects.

2 MATERIALS AND METHODS

The geometry of the forging dies and billets were modeled with the software SolidEdgeV14 and transferred to the FEM software FORGE 2008. Figure 1 shows the connecting rod used in the multi-directional process.

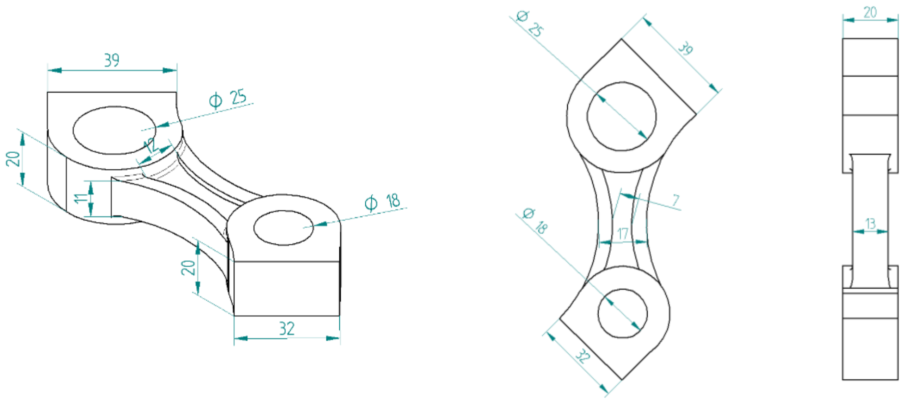


Figure 1. Model and dimensions of the connecting rod.

Numerical simulations were carried out using 38MnSiVS5 microalloyed steel and a hydraulic press. Triangular elements were used to discretize the tools and volumetric tetragonal elements to the billets. The workpiece was pre-heated at 1100°C and the tools at 200°C; data from the Forge 2008 database were used for heat transfer coefficient (2kW/(m^2°C)) and Coulomb friction coefficient of 0.15 to represent the lubrication of dies with a water-based lubricant. The speed of the tools was kept constant in 10 mm/s.

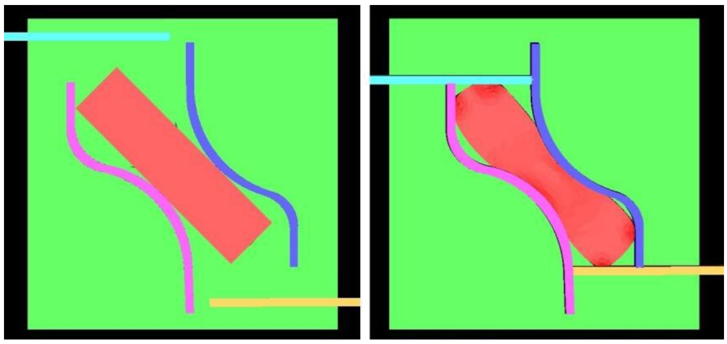


Figure 2. Movement of the tools in multi-directional forging.

The presented numerical simulation has been described in [14]. First, the model of multi-directional forging was designed. This process consists in the displacement of four tools (light blue, navy blue, orange and purple) in the horizontal plane on the lower die surface (green) as seen in Figure 2. Closing the tools generates the shape of the connecting rod and eliminates the need of preforms. Therefore, billets with rectangular cross section were used to reduce processing time and raw material costs.

After moving the horizontal dies, the upper die (yellow) is moved down vertically to complete the process (Figure 3), so the connecting rod is produced in a single step.

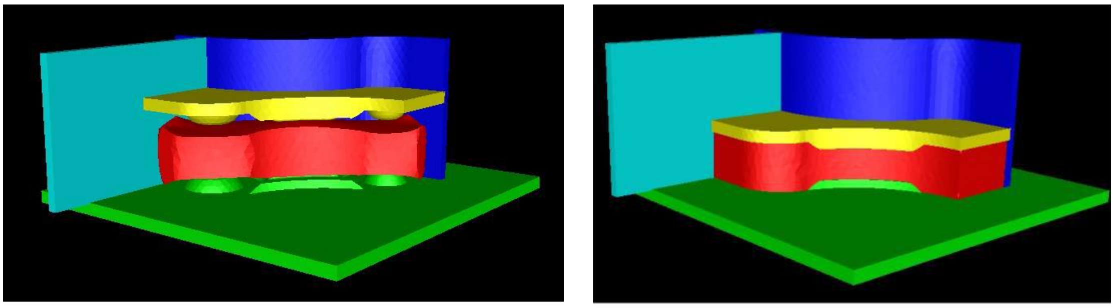


Figure 3. Displacement of the upper die.

Three rectangular-section billets, with the same volume and different dimensions, were evaluated in the multi-directional process simulation to achieve the best material flow, which avoids fold and other defects, and allows the complete flashless filling. Table 1 shows the dimensions and elements used to discretize each billet.

Table 1. Billets dimensions.

Billet	Length (mm)	Width (mm)	Thickness (mm)	Volume (mm^3)	Number of elements
1	105	28	17	49 980	30 211
2	87,7	38	15	49 989	30 110
3	124,95	20	20	49 980	30 213

Varying the billet dimensions it was possible to model three cases:

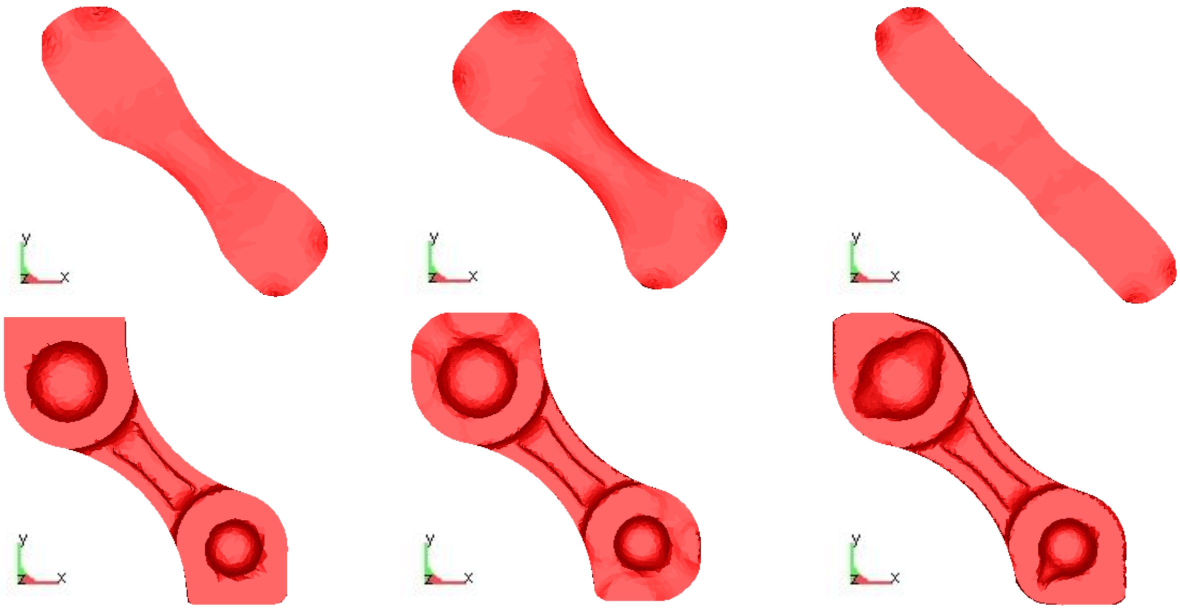
Case 1- Multi-directional forging with billet 1;
Case 2- Multi-directional forging with billet 2; and
Case 3- Multi-directional forging with billet 3.

3 RESULTS

The multi-directional forging allows the workpiece to form in one single step from the billet with a very simple geometry. The work performed by the tools in the horizontal plane makes possible to obtain the preform since they force the metal to locations that are more appropriate to correct fill the dies. After closing the tools, the final forming of the connecting rod is achieved by moving down the upper die against the fixed lower die. This process does not need any preform as necessary in the convencional forging, what decreases the prodution costs.

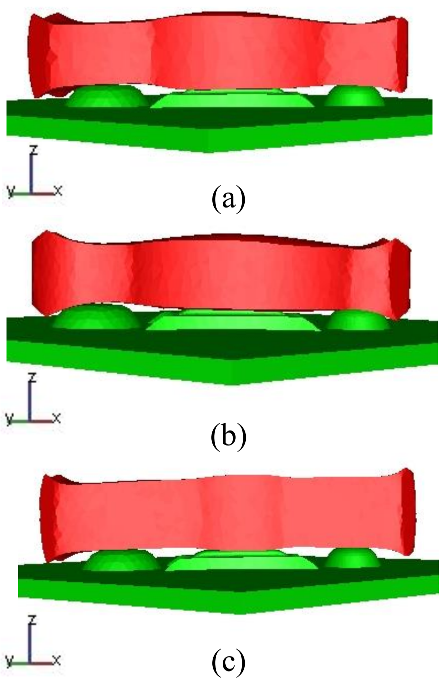
Figures 4 and 5 reveal the material flow in each simulated case, from the top and lateral view respectively. It can be observed that the flow is dissimilar from one case to another. Despite the movement of horizontal tools to force the metal to appropriate areas, this effect can be changed depending on the billet geometry what explains the different shapes obtained and confirm that the initial billet geometry plays a significant role in the process to obtain a suitable final part.

The Case 1 (Figure 4(a)) permits to obtain a flashless connecting rod in one-step, making it a viable and operational process. In addition, sharp corners can be formed and forging defects can be avoided. However, it is necessary a precise volume to fill the entire die impression, which implies in a greater concern with the billet separation process.



(a) (b) (c)

Figure 4. Top view of material flow for: (a) Case 1, (b) Case 2 and (c) Case 3.



(a)

(b)

(c)

Figure 5. Lateral view of material flow behaviors for all billets: (a) Case 1, (b) Case 2 and (c) Case 3.

The shape of the billet in the Cases 2 and 3 favors the development of forging defects. As it seen in Figure 6, a large width billet tents to present underfilling, and a very long billet tends to present folding besides underfilling. Both billets lean towards flash formation.

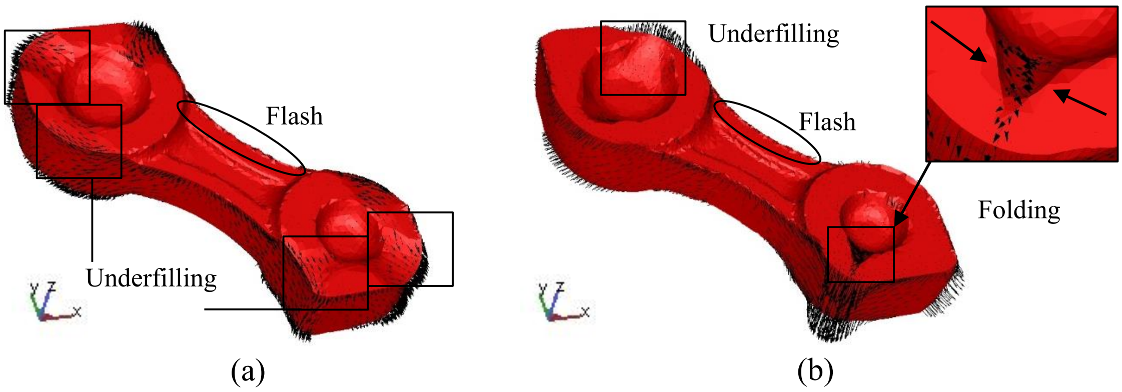


Figure 6. Folding defect in the forged part: (a) Billet 2 and (b) Billet 3.

Fold, or lap, is defined as surface-to-surface contact in the workpiece when the surface of the workpiece folds or collapses on itself [7]. Depending on the contact of the hot billet with the atmosphere an oxidation layer may be formed between the fold and impoverish the region by the decarburization. Fold is a risky defect when it is located inside the workpiece because it becomes invisible, and the product can be accepted by quality control. It should be noted that folding favors crack initiation, which may become a fracture causing product to fail during service.

Figure 6(b) presents the folding formation in the Case 3. Despite the forging process involve high compressive stresses, when the upper die moves down, additional stress states appear, which can result in a local inhomogeneous flow. As can be seen by the velocity vectors, the flow front next to the eye region of the connecting rod is opposed to another flow front very close; they collapse and result in an area of localized fold.

Another process variable that influences the material flow is the Coulomb friction coefficient. Numerical simulations were carried out for Case 2 and 3 using another friction coefficient of 0.30 to represent the condition of severe contact among the billet and tools. Figures 7 and 8 present the material flow for both coefficients from the top and lateral view, respectively.

The simulation results show that a higher friction coefficient tends to minimize underfilling and folding because the material flow is slowed in the region where the deformation is faster, and consequently, enables a homogeneous flow and minimizes forging defects.

In the Case 2 (Figure 7(a), the die cavity was almost completely filled with friction coefficient of 0.30. In case 3 (Figure 7(b), underfilling and fold are minimized with the higher friction coefficient. However, as seen in the Figure 8, the flash increases with increasing friction.

It is well known that increasing friction has some disadvantages, as the demand for greater forging loads, which contributes to premature wear of tools, increases the temperature and the need for energy. Hence, the friction between the tool/die and the workpiece during forging interferes directly on the tool life, as well as the equipment capacity.

Figure 9 shows that forging loads in Cases 2 and 3 are increased when the friction coefficient is increased from 0.15 to 0.30.

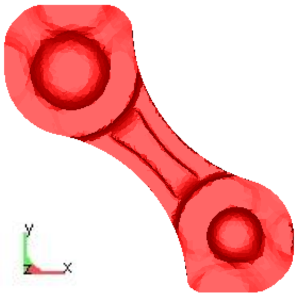
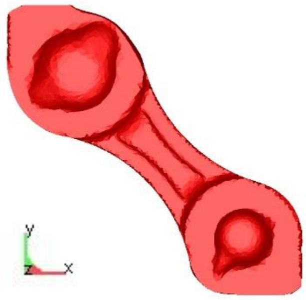
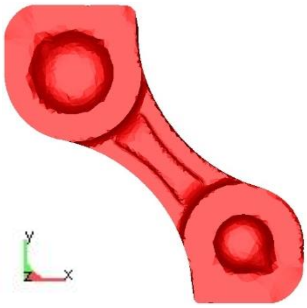
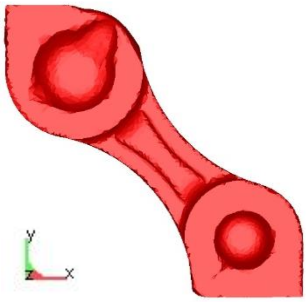
Friction coefficient	Case 2	Case3
0.15		
0.30		
	(a)	(b)

Figure 7. Metal flow in: (a) Case 2 and (b) 3 as a function of friction coefficient (Top view).

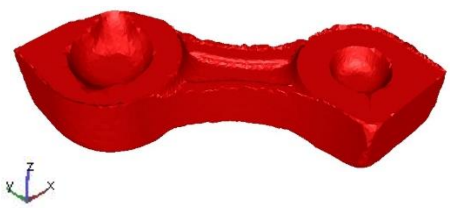
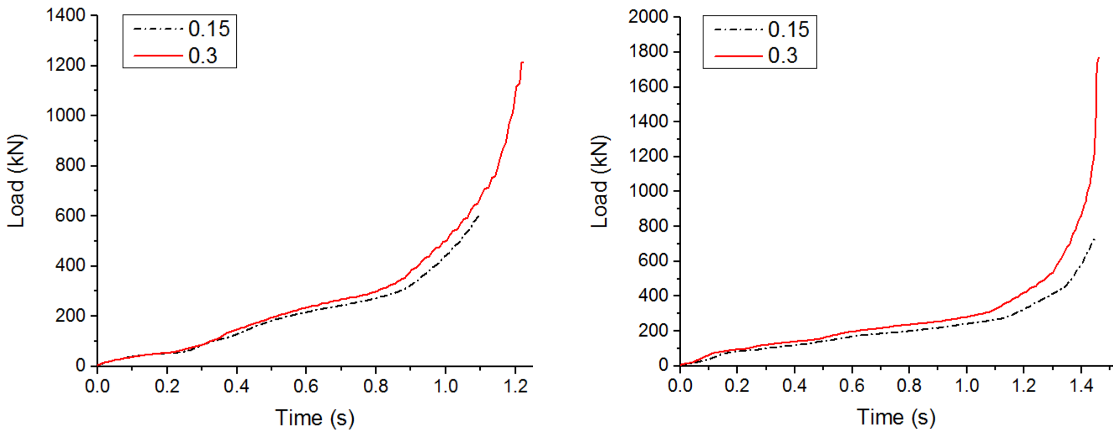
Friction coefficient	Case 2	Case3
0.15		
0.30		
	(a)	(b)

Figure 8. Metal flow in: (a) Case 2 and (b) 3 as a function of friction coefficient (Lateral view).

In both curves with the highest coefficient, it is observed a substantial increase of the load near the end of the process, which may be related to the formation of sharp corners in the connecting rod, and to the decrease of temperature caused by heat transfer between workpiece and dies, so the material flow becomes difficult due to the increase of flow stress, demanding higher pressures and forging loads.

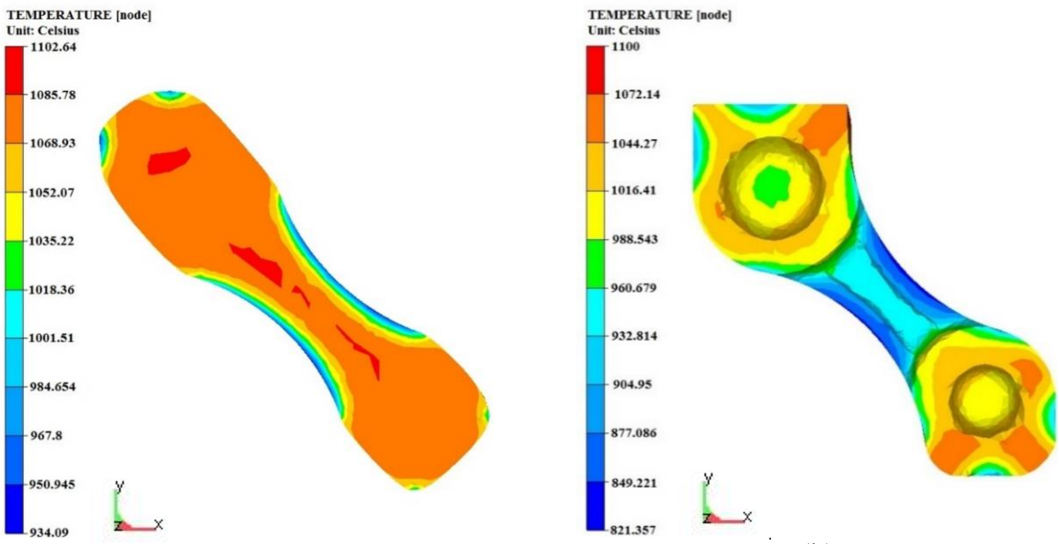
The maximum loads in Case 2 are 598kN and 1213kN for the low and high friction coefficients, respectively, while in Case 3, the maximum loads are 723kN and 1768 kN respectively. Case 3 presents higher forging loads because the billet is thicker than in other Cases (Table 1), so the upper die has a longer way to go down and to overcome friction for reaching the final height.



(a) (b)

Figure 9. Forging load in upper die in Cases 2 and 3 with different friction coefficients.

All the results show that Case 1 is the more viable and operational process, therefore the temperature, equivalent strain and von Mises stress distributions were analyzed for this case.



(a) (b)

Figure 10. Temperature distribution: (a) preform and (b) formed part.

Figure 10 shows the temperature distribution after closing the lateral tools and at end of the multi-directional forging of Billet 1. A significant heat loss and temperature decrease are observed in regions in contact with the lateral tools (Figure 10(a). At the end of the process (Figure 10(b), the temperature decreases further and becomes less uniform, due to the increasing contact between the upper die and the billet.

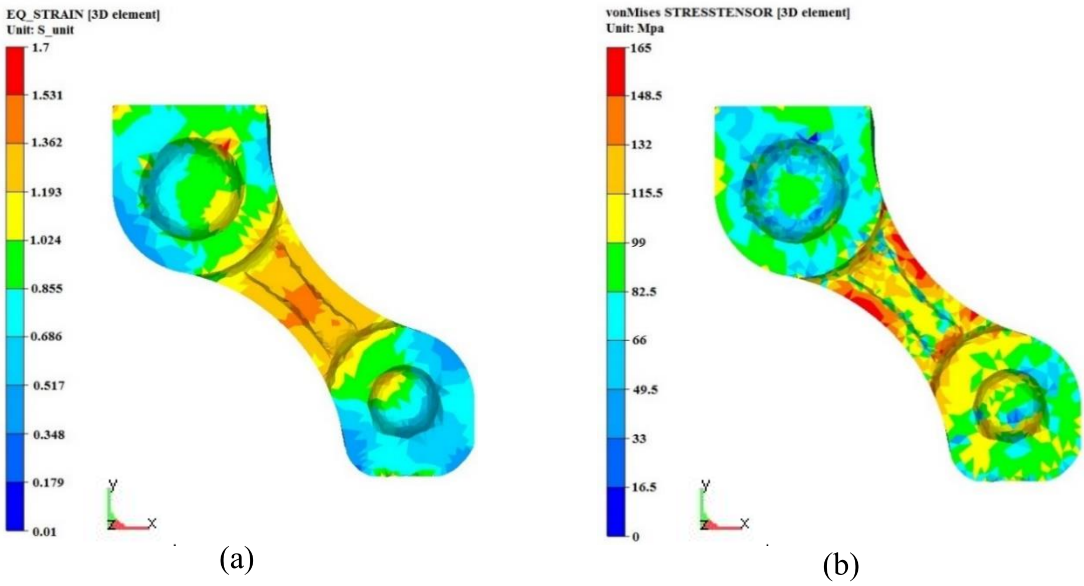


Figure 11.Distribution of (a) Equivalent plastic strain and (b) von Mises stress.

According to the distribution of equivalent strain in Figure 11(a), the deformation is mainly located in the center of the part (connecting rod stem), while the deformation in end regions is much smaller. Anyway, the multi-directional forging presented satisfactory values of equivalent strain around 1.5, which means that there is no risk of failure.

Many stress states can arise during forging due to the geometry of the tools and how forces are applied. If the stresses are high enough to difficult material flow, it can become unstable and localized defects are formed. Figure 11(b) shows the von Mises stress distribution, and as well as for the equivalent strain, the von Mises stress is mainly located in the center of the part and does not exceed 165 MPa.

4 CONCLUSIONS

- Numerical results showed that multi-directional forging is feasible because it can produce flashless products with sharp corners, which is not possible in conventional forging, and without the necessity of many steps or waste of raw material. However, it is essential to use billets with precise volume and dimensions.
- The billet geometry revealed to have great influence on the material flow. Billet 1 presents the ideal dimensions to produce a connecting rod completely formed and without defects.

- Simulation results showed that a higher friction coefficient tends to minimize underfilling and folding. However, it demands higher pressures and loads.
- The multi-directional forging presented satisfactory values of equivalent strain and von Mises stress, meaning that there is no risk of failure.

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