Finite Element Modeling Of Non-Constrained Closed Die Forging (Modified Upsetting) Using Deform 3d^{tm}

J.O. Obiko, F.M. Mwema

Abstract: This paper reports on the three-dimensional analysis of the upsetting process using Deform 3D simulation software. The influence of both die moving during the metal upsetting process denoted as modified upsetting process (similar to unconstrained closed die forging) was compared to conventional upsetting (when only one die moves) was investigated. From the upsetting simulation process the deformation load, stress and strain distribution results were obtained. The simulation results showed that the modified upsetting process had a lower deformation load and effective stress compared to the conventional upsetting process. However, the effective strain values were relatively similar for both cases. The effective stress and strain distribution were inhomogeneous, which was attributed to the changes in the deformation temperature. For sustainable industrial processes where energy consumption and production rates are significant, the modified upsetting process was recommended.

Keywords: Upsetting process, Deform 3D, deformation load, stress and strain distribution

1. INTRODUCTION

In metal forming process, upsetting (open die forging) process involves compressing the metal billet between two dies [1],[2]. The upsetting method can be utilised to obtain flow stress curves under different loading conditions. The flow stress behaviour describes the material response during the deformation process [3]. During the deformation process, the metal workpiece is subjected to complex plastic deformation [4]. The quality of the product manufactured is influenced by deformation conditions such as temperature and strain rate [2]. Tahir [2] showed that the interfacial friction between the workpiece and die causes inhomogeneous deformation. This leads to an inhomogeneous stress and strain distribution during the deformation process [5][6]. Hence, flow instabilities such as cracks and flow localisation are likely to occur affecting the quality of the product [7]. The influence of deformation conditions on metal flow behaviour has been widely reported in the literature [4][8]. This has been achieved through experimental and finite element analysis techniques. However, the effect of both the lower and the upper die moving at the same speed during the forging (upsetting in a non-constrained conditions) process has not been widely reported. To study the effect of die movement on metal flow behaviour during the deformation process, FEM simulation was conducted. A $42CrMo_4$ steel commonly used for the manufacture of vehicle engine parts such as crankshaft and spindles [4], was used. Specifically, the effect of lower and upper die moving at the constant speed (denoted as modified upsetting) on the metal flow behaviour was studied. Finite element method (FEM) using Deform 3D software was utilised to analyse the flow behaviour.

2. FINITE ELEMENT MODELLING

The theoretical formulations of finite element in Deform 3D^{TM} tool has been documented clearly in literature [9][10]. The upsetting simulation process was conducted using FEM Deform 3D software using the simulation parameters summarised in Table **1**. The workpiece and the die geometries were modelled using the in-built primitive geometry tool in the Deform 3D software.

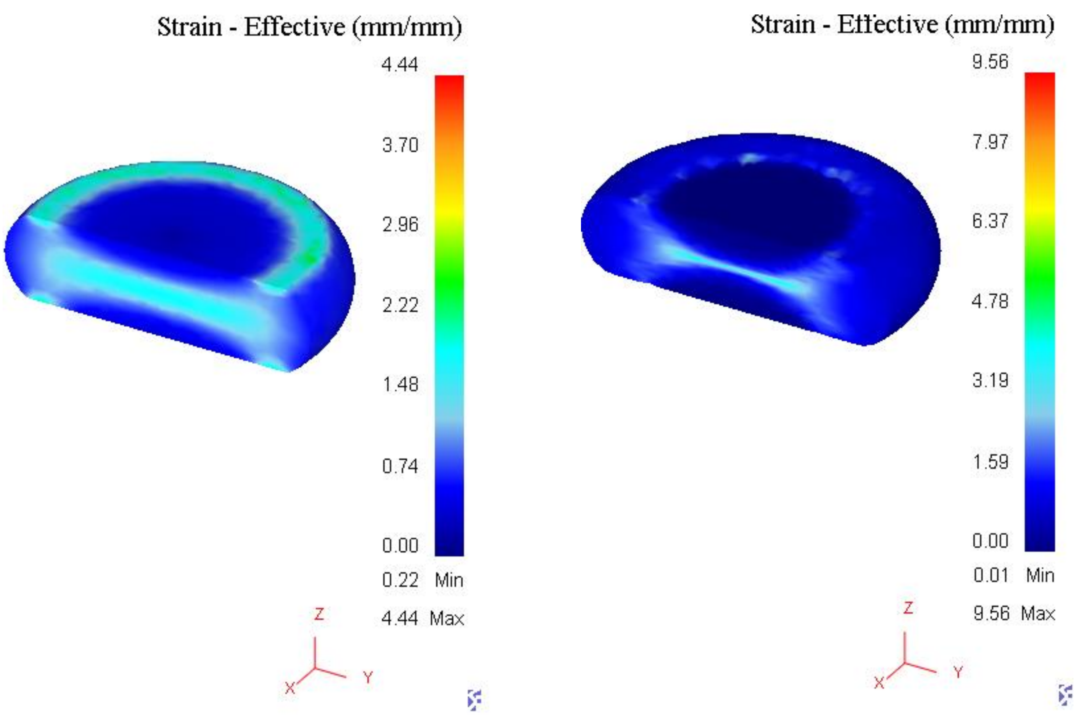
Table 1. *Simulation input parameters.*

Simulation Parameter	Value
Deformation temperature (°C)	1100
Die temperature (°C)	50
Die speed (mm/sec)	0.5
Convectional coefficient (N/s. mm °C)	0.02
Heat transfer coefficient (N/s. mm °C)	5
Height reduction (%)	67
Friction coefficient	0.3

3. RESULTS AND DISCUSSION

3.1. Load and temperature distribution

Figure 1 shows the deformed samples for both conventional and modified upsetting process after simulation to the deformation degree of 67%. From Figure 1a and 1b, it was observed that the maximum effective strain occurred at the centre height of the workpiece during the deformation process. This region experiences severe plastic deformation due to higher radial plastic strain which occurs at mid-height of the specimen [7]. It can be seen that during the conventional upsetting the severely deformed region had higher area compared to the modified upsetting process. This can be attributed to the uniform application of load from both directions (lower and upper dies). The temperature distribution was inhomogeneous as shown in Figure 2a and 2b for both upsetting deformation cases. Four points (point 1, 2, 3 and 4) were chosen to track the temperature distribution during the deformation process as shown in Figure 2. During the conventional upsetting process, a high-temperature decrease of ~ 1000 °C was observed at all the tracking points at the end of the deformation process. The decrease in temperature can be attributed to the temperature gradient between the die and the workpiece, or heat transfer from the workpiece to the environment. Point 1 (P1) had the highest rate of temperature decrease compared to the other points. Point 3 and 4 (P3 and P4) had relatively the same temperature decrease rate as shown in Figure 2a. In modified upsetting process point 1 had a temperature decrease of ~ 473 °C while in the other points the temperature increased. In point 2 (P2) the temperature increased by 1236 °C while point 3 and 4 the temperature increased by 724 °C and 573 °C respectively. The variation in temperature can be attributed to the increase in friction at the die-workpiece interface, which leads to the transformation of plastic work into heat hence increasing the temperature during deformation. To determine the required deformation loads, the flow stress is corrected using the friction correction factor. Numerical equations have been developed to determine the friction factor [11]. The load-stroke curves for both upsetting processes after simulation are shown in Figure 2c and 2d. It was observed that the deformation load for conventional upsetting process increased continuously with an increase in stroke. This may be attributed to the high generation of dislocation density hence increasing the deformation energy. During modified upsetting process rapid increase in the deformation load due to work hardening at the initial stages of deformation was observed. However, at a higher stroke (deformation) a balance between work hardening and dynamic softening was reached. At this stage, the flow curve exhibited a steady-state condition up to the stroke of 3.72 mm. This represents a typical flow curve obtained during the hot metalworking process. After 3.72 mm stroke, an increase in deformation load until the end of the simulation process was observed. This sudden increase in the deformation process can be attributed to a change of friction from dynamic to static friction [12]. Generally, the modified upsetting process had lower deformation loads compared to the conventional upsetting process.



a) Conventional upsetting b) Modified upsetting

Figure 1. *Deformed short cylinder at 1100 °C and die speed of 0.5mm/sec.*

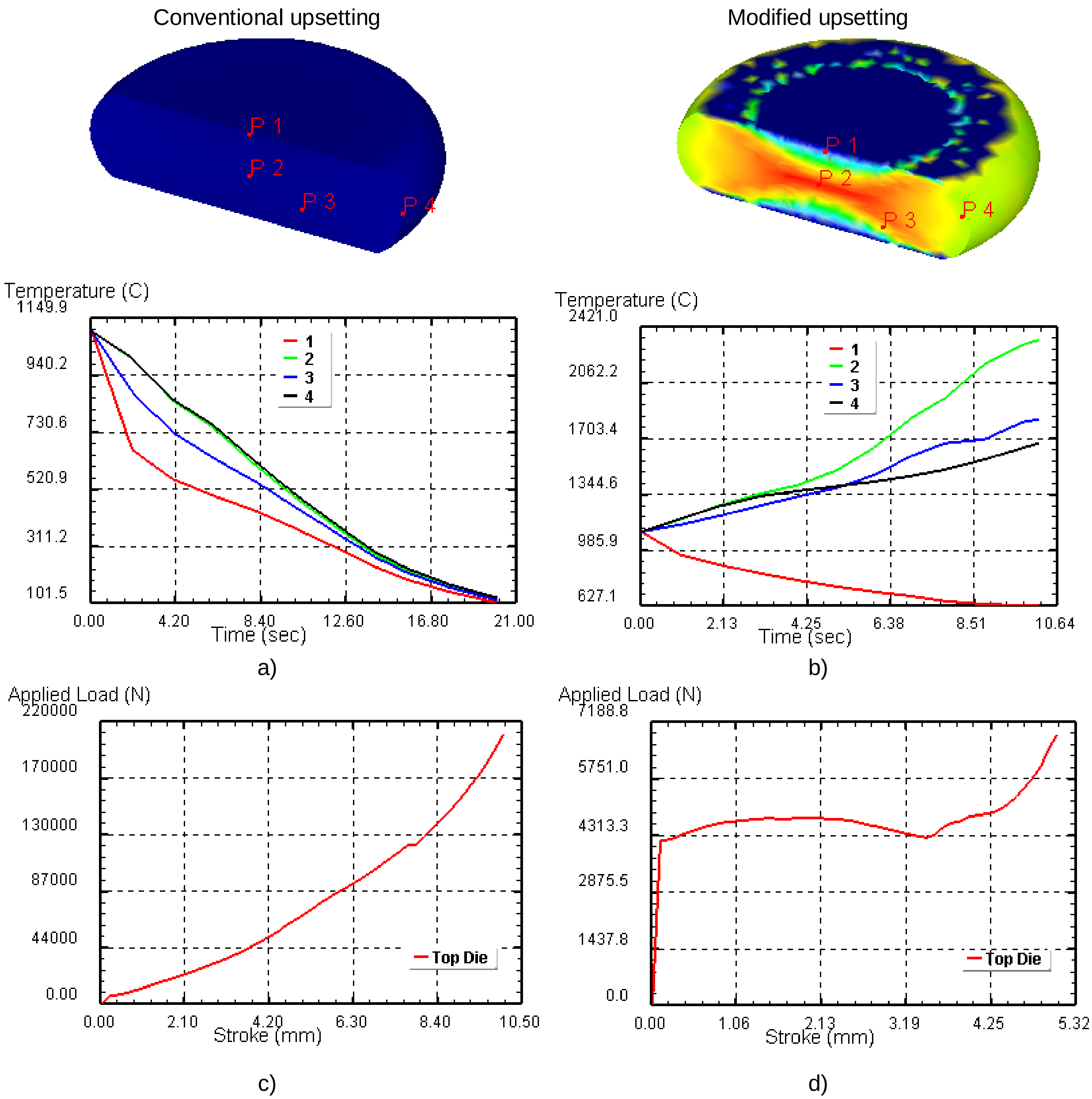


***Figure 2**.Load-stroke and temperature variation during the upsetting process.*

3.2. Effective stress and strain distribution

Figure 3 shows the stress and strain distribution of four tracking points on the deformed short cylinder after upsetting simulation. From Figure 3 the results show that the deformation process for both conventional and modified upsetting was inhomogeneous. After the deformation degree of 67%, the maximum effective strain was at the centre of the workpiece (point P2) in both upsetting cases as shown in Figure 3 a and b. This indicates that the region experienced severe plastic deformation, which leads to grain refinement [4]. The effective strain values varied at different points of the deformed workpiece. This variation in effective strain showed inhomogeneous deformation process. Similar observations during forging or upsetting process have been reported in the literature [5][6][13]. Research has shown that the inhomogeneous deformation process during hot deformation can be attributed to effects of friction, chilling and flow localisation [7]. Point 1 had the lowest effective strain value in both cases due to the chilling effect. The intermediate points (point 3 and 4) showed a relatively similar trend of the effective strain. Points 2, 3 and 4 showed an increase in the effective strain with an increase in the deformation degree. In general, the modified upsetting process exhibited higher effective strain compared to the conventional upsetting for all the tracking points (Figure 3 a-b) after the deformation process. However, modified upsetting had a shorter deformation time, which can be attributed to the contribution of both dies. From an industrial perspective, this reduces production cost and increases productivity. From Figure 3 c and d, the stress distribution was also inhomogeneous. The maximum effective stress for the conventional upsetting process occurred at the boundary that experienced lower and higher effective strain (point 3) during the initial stages of deformation (< 8.40 seconds) as shown in Figure 3c. However, at a higher degree of deformation, point 2 had the highest effective stress. At deformation time of greater than 8.40 seconds, point 3 and 4 had relatively similar effective stress values. The increase in effective stress can be attributed to the formation of precipitates as the deformation temperature decreases (Figure 2a), hence hindering the deformation process. For modified upsetting process, maximum effective stress occurred at point 1 during the initial and final stages of the deformation process as shown in Figure 3d. At the initial stage, the higher stresses observed in point 1 can be attributed to lower deformation temperature due to the chilling effect between the dies and the workpiece [7]. After deformation time of 2.13 seconds the effective stress decrease which may be due to the occurrence of dynamic softening mechanism. Further increase in the deformation process leads to an abrupt increase in the effective stress in point 1, this may be attributed to an increase in the interfacial friction [12]. In Point 2, 3 and 4, effective stress increased during the initial stages of deformation up to the deformation time of 2.13 seconds. Thereafter, a decrease in effective stress was observed until the end of the deformation process. The decrease in the effective stress can be attributed to heat generation as plastic deformation work is converted into heat [11], hence increasing the deformation temperature as shown in Figure 2b. Material softening occurs due to internal heat generated hence decreases effective stress. Under the modified upsetting process, lower effective stress was observed compared to conventional upsetting. This implies that under the same deformation conditions and workpiece, the modified upsetting process requires a lower capacity forging machine compared to a conventional upsetting machine.

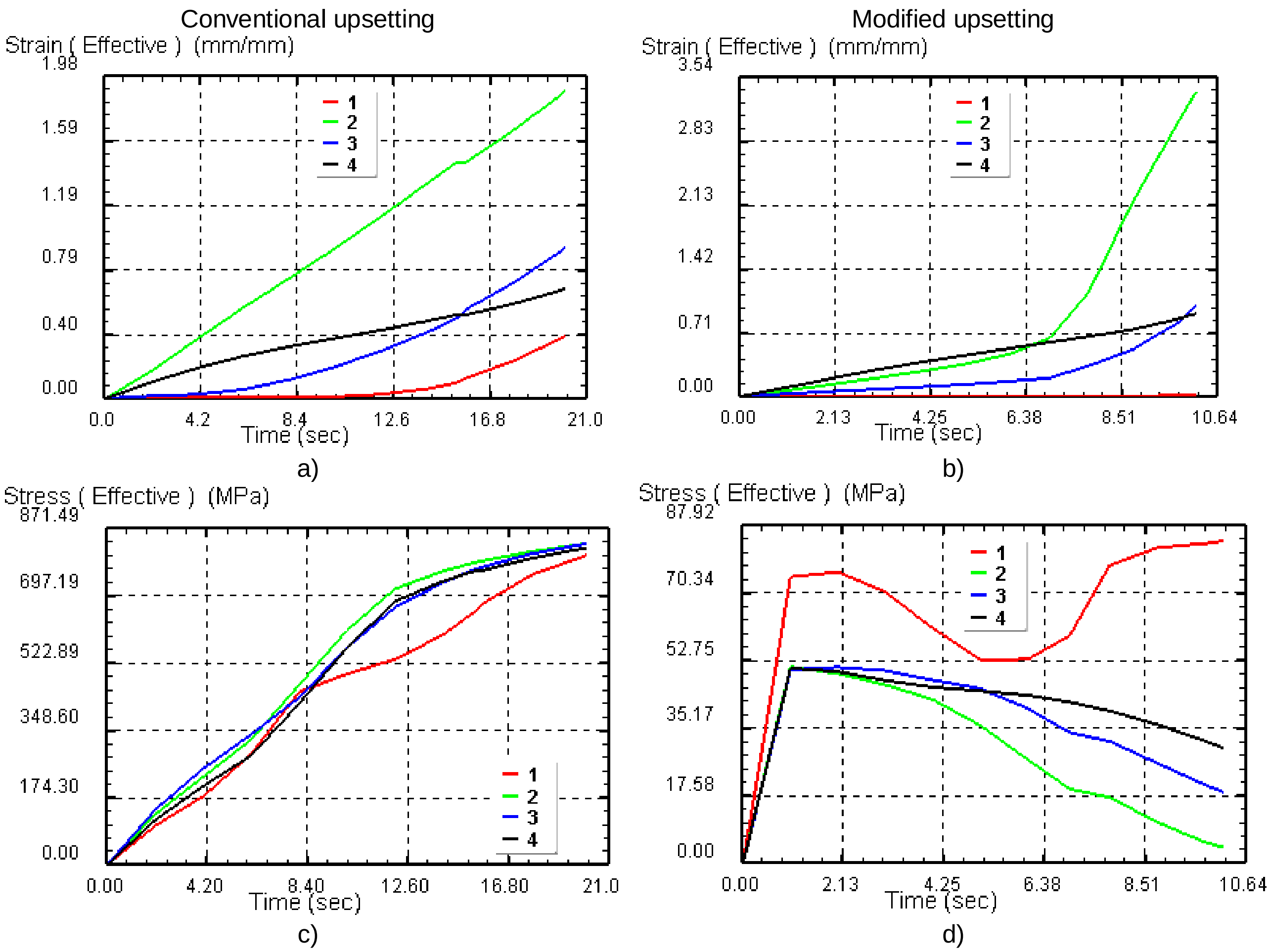


Figure 3. *Effect of die movement on (a-b) the effective strain distribution and (c-d) effective stress distribution.*

The effective stress and strain distribution curves for the four points indicates that the deformation process was inhomogeneous. This can be confirmed further as shown in

Figure **4**. The figure shows the standard deviation of the effective stress and strain distribution, hence inhomogeneous deformation occurred during the deformation process. The inhomogeneous deformation can be attributed to friction effects at the die-workpiece interface which leads to internal heat generation. Thus, effective strain and deformation become inhomogeneous. The generated heat is lost through the specimen surface. This is so because the internal temperature is higher than the surrounding temperature. The flow inhomogeneity increases with the degree of deformation [11].

Conventional upsetting	Modified upsetting

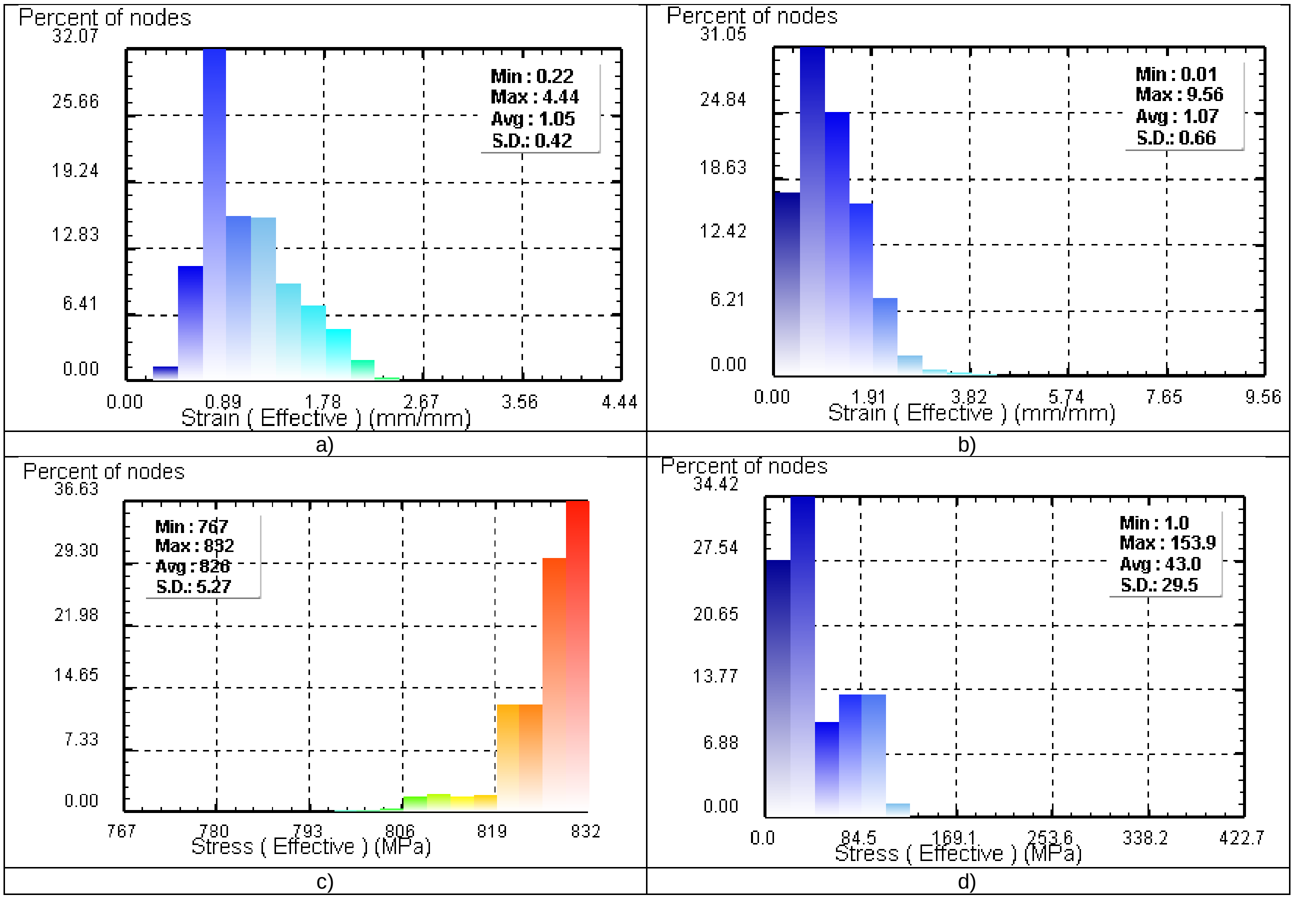


Figure 4.*Effect of die movement on the (a-b) effective strain distribution and (c-d) effective stress distribution.*

4. CONCLUSION

From the simulation results of the upsetting process using Deform 3D simulation software, the following conclusions were drawn:

1. The deformation temperature across the deformed sample was inhomogeneous. The load-stroke curves showed that the deformation load increased with an increase in the stroke (deformation) for the conventional upsetting process. While in the modified upsetting process the load-stroke curve exhibited a typical flow stress curve during the metalworking process. In this case, the load reaches a steady-state condition after initial work hardening stage due to the balance between work hardening and dynamic softening.
2. The effective stress and strain distribution across the deformed sample were also inhomogeneous. This was attributed to the changes in the deformation temperature during the upsetting process.
3. The modified upsetting process had the lowest deformation load and effective stress values compared to the conventional upsetting process. However, in both upsetting processes, effective strain values were relatively similar. For industrial application, modified upsetting process was recommend.

REFERENCES

[1] N. Radi, M. Kraišnik, and S. Trifkovi, “Numerical Analysis of Free Upsetting Cylinder,” vol. 10, no. March, pp. 239–243, 2011.

[2] T. Altinbalik and Y. Çan, “An upper bound analysis and determination of the barrelling profile in upsetting,” Indian J. Eng. Mater. Sci., vol. 18, no. 6, pp. 416–424, 2011.

[3] P. Christiansen, P. A. F. Martins, and N. Bay, “Friction Compensation in the Upsetting of Cylindrical Test Specimens,” Exp. Mech., vol. 56, no. 7, pp. 1271–1279, 2016.

[4] Y. C. Lin, M. S. Chen, and J. Zhong, “Numerical simulation for stress/strain distribution and microstructural evolution in 42CrMo steel during hot upsetting process,” Comput. Mater. Sci., vol. 43, no. 4, pp. 1117–1122, 2008.

[5] J. O. Obiko, F. M. Mwema, and E. T. Akinlabi, “Strain rate-strain/stress relationship during isothermal forging: A Deform-3D FEM,” Eng. Solid Mech., vol. 8, pp. 1–6, 2019.

[6] J. O. Obiko, F. M. Mwema, and M. O. Bodunrin, “Finite element simulation of X20CrMoV121 steel billet forging process using the Deform 3D software,” SN Appl. Sci., vol. 1, no. 9, p. 1044, 2019.

[7] J. Rasti, A. Najafizadeh, and M. Meratian, “Correcting the stress-strain curve in hot compression test using finite element analysis and

Taguchi method," Int. J. ISSI, vol. 8, no. 1, pp. 26–33, 2011.
[8] Y. M. Antoshchenkov and I. M. Taupek, "Computer simulation of axisymmetric upsetting," Steel Transl., vol. 45, no. 1, pp. 38–41, 2015.
[9] S. I. Oh, "Finite element analysis of metal forming processes with arbitrarily shaped dies," Int. J. Mech. Sci., vol. 24, no. 8, pp. 479–493, 1982.
[10] M. Kukuryk, "Analysis of deformation and damage evolution in hot elongation forging," Arch. Metall. Mater., vol. 57, no. 2, pp. 417–424, 2012.
[11] R. W. Evans and P. J. Scharning, "Axisymmetric compression test and hot working properties of alloys," Mater. Sci. Technol., vol. 17, no. 8, pp. 995–1004, 2001.
[12] Y. P. Li, E. Onodera, H. Matsumoto, and A. Chiba, "Correcting the stress-strain curve in hot compression process to high strain level," Metall. Mater. Trans. A Phys. Metall. Mater. Sci., vol. 40, no. 4, pp. 982–990, 2009.
[13] Z. J. Zhang, G. Z. Dai, S. N. Wu, L. X. Dong, and L. L. Liu, "Simulation of 42CrMo steel billet upsetting and its defects analyses during forming process based on the software DEFORM-3D," Mater. Sci. Eng. A, vol. 499, no. 1–2, pp. 49–52, 2009.