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Effect of aspect ratio on the metal flow behaviour during forming process: A numerical simulation approach

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ABSTRACT

This paper presents results on the effect of aspect ratio on the flow stress of 42CrMo4 steel using Deform™ 3D Version 11 simulation software. The FEM simulation process conditions were upsetting temperature of 1000 °C and 10 s^{-1} strain rate. The sample aspect ratios (height/diameter) varied within commonly used ranges during conventional Gleeble experimentations. The aspect ratio did not affect the flow stress behaviour during forming. Generally, the forming conditions influence the flow stress-strain field and distribution behaviour, causing inhomogeneous deformation. A negligible effect of aspect ratio on typical industrial forging process is only attainable between 1.0 and 2.0. The implications of the results for industrial forging are elucidated.

Introduction

The integrity of structural components for the industrial application depends on the forming process, i.e., forging. Forming processes offer unique opportunity to shape parts and develop reproducible microstructure [1]. During metal forming, complex stresses are applied which affects the metal flow. The microstructure of the final product depends on the forming conditions [2–4]. Hence, optimisation of process parameters is crucial in ensuring the quality of the final product is desirable with negligible defects [1]. This reduces the adverse effects on structural and functional properties, thus negligible compromise on structural integrity [5–7].

Constitutive modelling has been used to elucidate the flow behaviour and mechanism associated with hot deformation processes [4,8,9]. It assesses the intrinsic workability of materials [10] with complex stress–strain states due to the effects of process variables and parameters [11,12]. Thermo-mechanical equipment simulates the metal forming processes to predict flow behaviour and mechanisms [13,14] with constant aspect ratio of 1.5 during forging [15,16]. However, different aspect ratios have been used to date [17,18] but the validity of the flow stress and the effects of different aspect ratios are seldom addressed. Therefore, the effect of varying aspect ratios on metal flow behaviour during upsetting of 42CrMo4 steel was simulated using finite element method (FEM) with DEFORM™ 3D package and compared with experimental data from the Gleeble®. The simulation used seven cylindrical test samples. The 42CrMo4 has excellent strength-toughness synergy with high wear resistance. Hence, it is widely used to manufacture crankshafts, ring

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gears, crowbars, and spindles [19,20].

The aim of the study is to understand the intricate interplay between aspect ratio and metal flow behaviour by numerical simulation. Conventionally, the selection of aspect ratios for metal forming processes relied mostly on experiential rules of thumb. However, there is the need for standardization to ensure certain ranges are applicable for all materials. Hence the gap in research which is being addressed using numerical methods and validated with experimental data to avoid discrepancies in the overall analysis. With the advent of numerical simulation as a robust tool in engineering, it offers an opportunity for deeper insight into complex phenomena that are not easily captured by empirical methods. By harnessing the power of numerical modelling, one can shed light on the precise and comprehensive influence of aspect ratio on metal flow behaviour which is largely missing in the literature. This approach resonates with industrial practice, holding promise for enhancing the efficiency and effectiveness of metal forming processes across diverse sectors. The assessment of the effects of aspect ratio on metal flow behaviour provide the needed pathway for the optimization of metal forming processes. Thus, fostering improvements in product quality, reduction in material wastage, and increased productivity. The implication of this study lays the groundwork for the development of advanced computational models and predictive tools for the design and optimization of forming processes.

FEM model validation

The quality of forged products depends on the experience. The flow stress analysis and process parameter determination are long and time-consuming with high production costs [21]. Simulations have revolutionised the manufacturing industry reducing the process constraints associated with metal flow behaviour [22–29]. The accuracy of FEM simulations depends on the experimental data validation. Constitutive equations are used for analysing metal flow stress behaviour as input codes for the simulation [4,9,30]. However, experimental data depends on loading conditions and sample geometry which were carefully used in this study with the DEFORM™ 3D Version 11 software.

Simulation details

The workpiece and two dies were designed using primitive geometry module with properties within the software database. Fig. 1 shows the FEM model and the deformed sample, whereas Table 1 shows the simulation conditions for the 42CrMo4 structural steel. For a typical forming process, the deformation is better observed in a single-phase domain which is close to the Ac_3 temperature for structural steels. In the case of 42CrMo4 structural steel, the single-phase is within the austenite region with AC_3 approximately 900 °C. Thus, the forging simulation was within the austenite region and comparable to published literature [31]. The upset process was done at strain rate of 10 s^{-1} for all test samples with 60 % final deformation. The results were validated using experimental data [32].

Results, discussion, and practical implications

Results and discussion

The stress and strain distributions from the FEM simulation are in Figs. 2 and 3. All The samples, irrespective of the aspect ratio had similar stress/strain distribution after deformation. The contours from the stress–strain distribution show that an inhomogeneous upsetting process due to dynamic interfacial friction [33], showing the different deformation regions. These regions have distinct

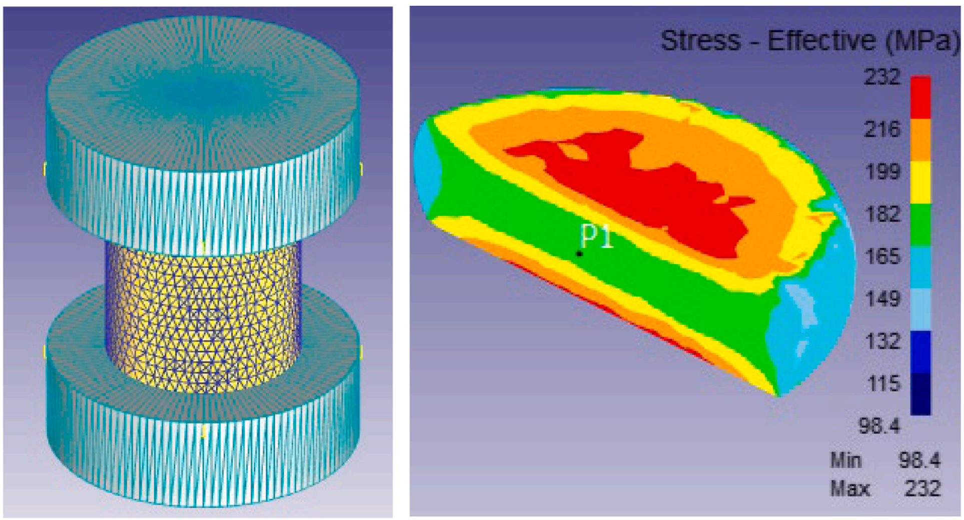

Fig. 1. (a) Finite element set-up model, and (b) workpiece after deformation where P1 is the tracing point for the flow stress.

Table 1
Forging parameters for simulation.

Description	Value
Workpiece material	42CrMo4 steel
Workpiece height h (mm)	10, 14.4, 18.2, 22.4, 27,32,56
Workpiece diameter d (mm)	10, 12, 14, 16, 18, 20, 28
Aspect ratio (h/d)	1,1.2,1.3, 1.4, 1.5, 1.6, 2.0
Forging workpiece temperature (°C)	1000
Strain rate (s^{-1})	10
Forging die temperature (°C)	300
Coefficient of heat convention (N/(s mm °C))	0.02
Coefficient of heat transfer (N/(s.mm °C))	5
Coefficient of friction (lubricated)	0.3
Workpiece discretised elements	35,022
Element nodes	6920
Simulation environment (°C)	25
Friction type	shear

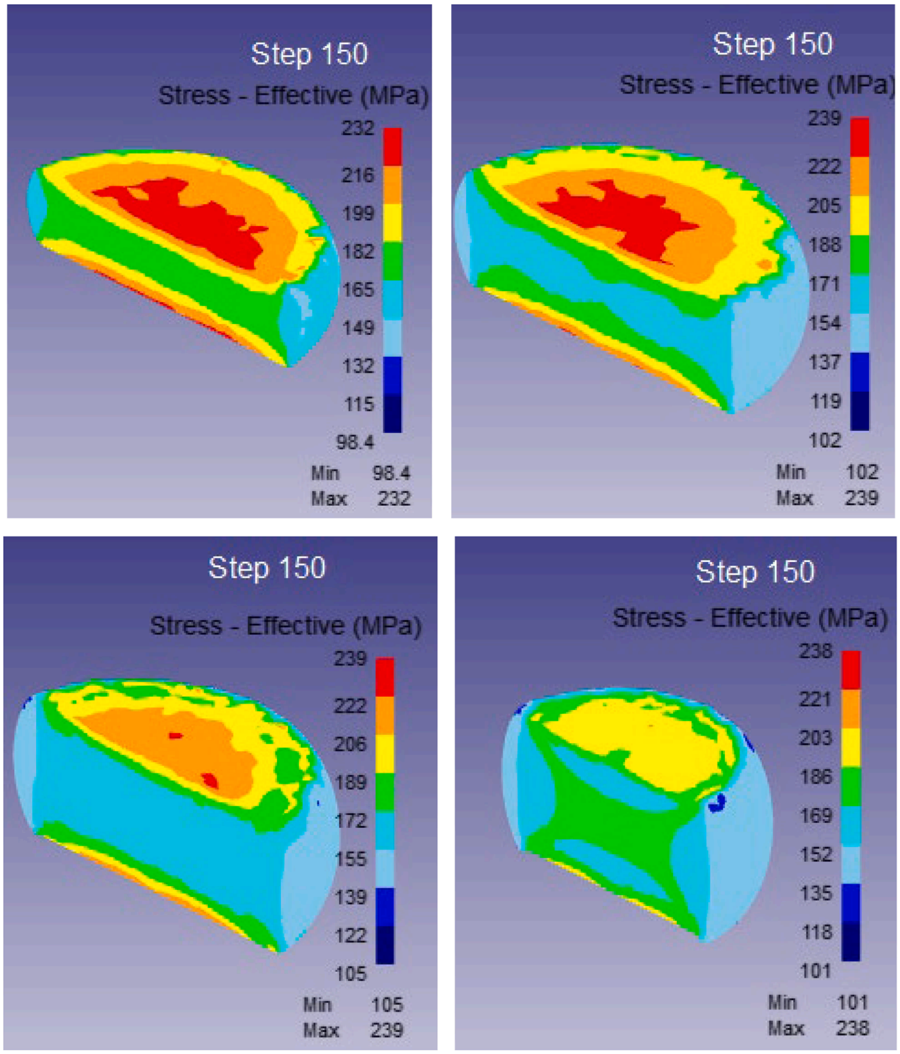

Fig. 2. The effect forming conditions on the stress distribution showing aspect ratio of: (a) 1.0, (b) 1.3, (c) 1.6 and (d) 2.0.

microstructures affecting structural integrity. However, through process parameter and variable optimization, better structural and functional properties can be tuned. Generally, the friction coefficient increases with strain during compression [34].

The simulated flow stress-strain curves at the upsetting temperature of 1000 °C and strain rate 10 s^{-1} with varying aspect ratios is

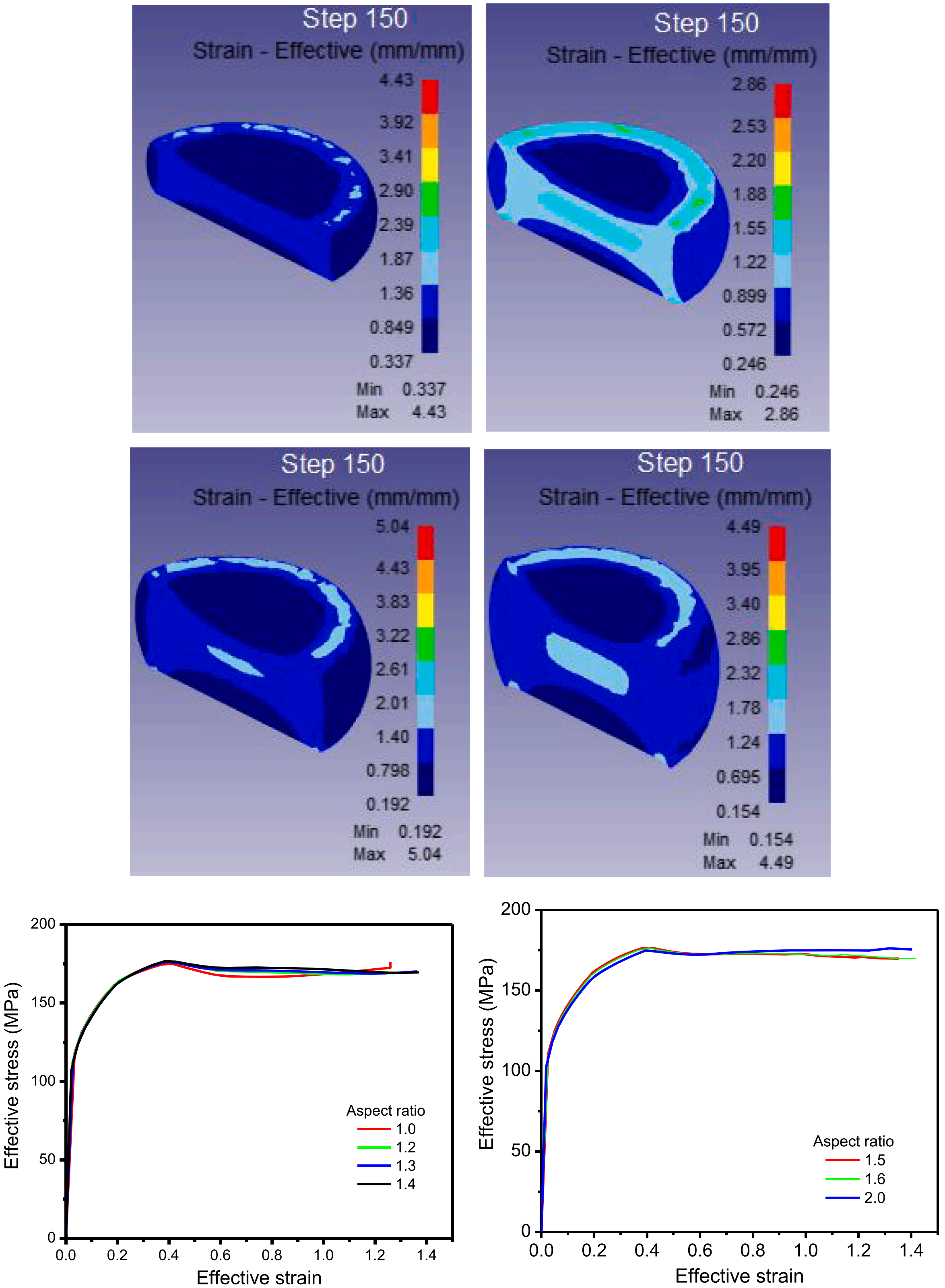

Fig. 3. Forming process conditions on strain distribution with aspect ratios of (a) 1.0, (b) 1.3, (c) 1.6, (d) 2.0 and peak stresses given in (e) and (f).

given in Fig. 3(e) and (f). The characteristic dynamic recrystallisation (DRX) behaviour was observed for all test conditions. The curves increased rapidly with increasing strain to ∼40 % of deformation and peaked. Strain work hardening (WH) was the main deformation mechanism. High dislocation densities occur at relatively low strain. After the peak flow stress at ∼0.4 strain, there was gradually decrease in flow stress with increasing strain until a steady stress state was attained at 60 % strain. Thus, a dynamic recovery (DRX) was observed for the curves with WH + DRX as the deformation mechanisms with low flow stress [35]. There was a strong correlation between the FEM simulations and the experimental data (Fig. 3).

Based on aspect ratio between 1.0 and 2.0, the peak stresses ranged between 174.6 and 176.6 MPa with corresponding strains from 0.38 to 0.41. This showed negligible effects of aspect ratios on metal forming process. Generally, the variation between the highest and lowest peak stress is less than 1.26 % which is not statistically significant as the standard deviation is really negligible. Similar flow patterns (stress and strain distribution) and trends in deformed samples has been observed [36]. Although, experiments based on the Gleeble®, aspect ratios between 1.2 and 1.5 are generally accepted, the suggested range of 1.0–2.0 did not show any large discrepancies and mechanisms associated with the metal flow behaviour. The aspect ratios that are above the 1.5 threshold did not have any discernible trend or effect on the flow stress. Hence, the material constants and activation energy derived from the constitutive equations according to [37] did not change. Thus, these values are widely used to analyse flow stress behaviour of most materials as they are within acceptable limit preventing under—or over estimation of the stress—strain behaviour.

Practical implication on industrial application

Unlocking the practical significance of aspect ratios in metal forming transcends mere theoretical comprehension. It presents tangible and practical advantages for metal forming industries. These could be in optimized tool design [25–28], process parameter optimization, enhanced product performance, new rational material design, and predictive modelling based on simulations [29]. In terms of optimized tool design, insights from understanding the effect of aspect ratio on metal flow behaviour can inform the design and optimization of forming tools [25–28]. By tailoring the tool geometry to accommodate specific aspect ratios [4], manufacturers can minimize material waste [38,39], reduce production time, and enhance the overall efficiency of the forming process [22–25,40, 41]. This optimization can lead to cost savings and improved competitiveness in the market [42–44].

Metal forming processes often involve many processing parameters such as temperature, pressure, strain rate, strain, coefficient of friction and speed. Understanding how aspect ratio influences metal flow behaviour enables engineers to fine-tune these parameters for maximum effectiveness. By optimizing process parameters based on the aspect ratio of the material being deformed, manufacturers can achieve higher product quality, tight tolerances, and reduced scrap rates. These are critical for product performance. In industries where product performance is critical, such as aerospace and automotive sectors, the ability to control metal flow behaviour can have profound implications. Thus, manufacturers can design components with optimized aspect ratios to enhance structural integrity, fatigue resistance [7,45,46], and overall performance under operating conditions and across microstructural length scales [41,47]. This can lead to safe and more reliable products, thereby increasing overall satisfaction.

The findings can inform materials development efforts aimed at enhancing formability and processability [4,9,48–52]. By understanding how different materials respond to varying aspect ratios, researchers can tailor material compositions and microstructures to facilitate easy deformation and flow during forming operations. This can expand the range of materials available for industrial applications and open up new possibilities for lightweighting and performance optimization. The process can be further enhanced and developed through predictive modelling and simulations. Thus, advanced computational models based on the insights gained can be integrated into simulation softwares complimentary to DEFORM™ in industrial settings. By incorporating accurate predictions of metal flow behaviour under different aspect ratios, one can simulate and optimize forming processes virtually, reducing the need for costly trial-and-error experimentation [29]. This accelerates product development cycles, lowers development costs, and enables rapid adaptation to changing market demands. Thus, understanding the effects of aspect ratios on the deformation process and leveraging that insights, one can drive innovation, improve competitiveness, and deliver higher quality products to meet the evolving needs of most of the industries.

While this study focused on analysing the varying aspect ratio of structural steel, it is essential to note that the aspect ratio, being a function of geometry, applies universally across all metals and alloys that have been studied over the years. However, the issue is to establish the range that is applicable for no discrepancies. This has been achieved. Therefore, as long as the aspect ratio falls within the stated ranges and deformation processes are done within a single-phase domain, no significant and adverse challenges should be encountered.

Conclusion

Based on the FEM simulation, the flow stress increased until the peak stress was attained and then drops to a steady state as the strain increases. The curves showed dynamic recrystallisation behaviour. The stress and strain distribution were non-uniform with inhomogeneous deformation behaviour, which is attributed to the interfacial frictional forces between the workpiece and the die generating internal heat. The aspect ratio between 1.0 and 2.0 had no significant effect on flow behaviour and mechanisms of the 42CrMo4 structural steel. The results were comparable to 1.2–1.5 recommended for experimentation using the Gleeble®.

The practical implications for large scale industrial applications are highlighted. Critical examples are on tool design and process parameter optimization, enhanced product performance, new rational material design, and predictive modelling based on simulations.

CRediT authorship contribution statement

Japheth Obiko: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Brendon Shongwe:** Conceptualization, Writing – review & editing. **Nicholas Malatji:** Conceptualization, Writing – review & editing. **Michael Bodunrin:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Desmond Klenam:** Conceptualization, Formal analysis, Writing – review & editing, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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