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INVESTIGATING THE EFFECT OF HEAT TREATMENT ON THE COLD FORGING OF 27MNB4 STEEL VIA CALPHAD METHODOLOGY AND FEM

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Highlights

- It is observed that microstructural differences affect the cold formability and stress distribution of 27MnB4 steel. Furthermore, creating small and round cementite particles in the ferritic matrix by the annealing treatment enhances the formability.
- It is possible to simulate the annealing treatment and the effect of annealing treatment on the cold forming of 27MnB4 steel with CALPHAD (Calculation of Phase Diagrams) and FEM-based (Finite Element Method) softwares.

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ABSTRACT: As a material forming method, cold forging is preferred due to the reasons like absence of a heating step and high surface quality. Recently, the finite element method (FEM) has received growing attention for controlling and predicting final material properties for cold forging applications. FEM combines microstructure evolution models with failure criteria, thus providing solutions to complicated problems in the modern cold forging industry. The fastener industry extensively utilizes cold forging, in which manganese and boron-containing steels like 27MnB4 can be formed to obtain high mechanical properties. The current study investigates the effect of two different heat treatments, namely softening and spheroidizing annealing, on the formability of 27MnB4 bolts. Softwares such as Thermo-Calc 2022a and Forge NxT 3.2 were used to predict the microstructure of the wire rod and evaluate the cold forming process of the same rod under two different heat treatment conditions. Therefore, the current study also provides a relationship between microstructural features and the cold formability of 27MnB4 steel. The microstructure of 27MnB4 is predicted by CCT diagrams. The predicted microstructure corresponds to the microstructure of 27MnB4 samples taken from the production line. In addition, temperature, von Mises stress, and equivalent strain distributions for 27MnB4 steel in the hot rolled state were calculated higher than in annealed states due to the differences in the microstructure. These results demonstrate that computational material engineering methods and simulation techniques could be practical tools for cold forming processes.

Keywords: 27MnB4, Cold Forming, Finite Element Method, Forging Simulation, Computational Materials Engineering

1. INTRODUCTION

Bolts are representative fasteners broadly used in assembling parts and complex structures. Developing high-strength and eco-friendly bolts is crucial to saving energy and addressing environmental concerns [1]. Steel wire rods are often preferred as starting materials for manufacturing bolts. After the hot rolling of wires, they are laid onto a cooling conveyor that provides controlled cooling by airflow. In the final stage, they are formed into coils and supplied to manufacturers [2].

Critical transformation temperatures (CTT) and cooling rates significantly influence the microstructure and the properties of the final product in many processes, including wire rod production.

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Therefore, such parameters help to design the optimum processing conditions for manufacturing steels with superior properties. For instance, CTT gives insights into processing temperatures, and they are practical tools for determining the desired cooling requirements [3]. Although computational methods can determine some parameters, data obtained by such practices must be reliable to get a positive outcome. On the other hand, acquiring this data via experimental testing can be costly and time-consuming. To this end, CALPHAD-based computational tools such as Thermo-Calc software aid the process design stage by performing thermodynamic and thermokinetic calculations that generate reliable materials data. In addition, such tools reduce the number of experiments and tests, resulting in a more economical and practical process [4, 5, 6].

Wire rods are deformed by forging to obtain bolts. Forging is a process that changes the shape of metal via pressure to get desired mechanical properties, shapes, and sizes. Especially with the improvements in forging technology, complex parts like bolts and nuts can be formed with better mechanical properties and accurate dimensions [7]. For the bolt industry, cold forging is a favourable method since heating is unnecessary, surface precision is optimum, and the service life of the expensive dies can be preserved via cold forging [8]. However, the formation of cracks during the cold forging of complex geometries can create deleterious problems and undetected defects on cold forged fasteners may cause serious problems. Therefore, it is essential to understand the crack evolution of cold forged fasteners for an efficient forming operation [9]. Additional annealing heat treatment steps may be needed to avoid crack evolution during cold forming operations. In addition, annealing treatment can be applied to fasteners for improved deformability. Spheroidization annealing (650-700°C) is one of the most common treatments for fastener manufacturing, in which lamellar cementite in pearlite structure transforms into granular carbides. As the degree of spheroidization increases, the ductility and deformability of the material also increase. In addition to spheroidization annealing, the soft annealing process can be applied to make the steel soft enough for cold forming. During soft annealing treatment (700-900°C), the cementite lamellae in pearlite will spheroidize, creating small and round cementite particles in the ferritic matrix [10].

In recent years, the Finite-Element Method (FEM) has become a powerful tool to analyse metal deformation and predict numerous failures during forming processes [11]. Software that uses FEM is combined with models of microstructure evolution, tool wear and fracture criteria. As a result, solutions to complicated problems in forging technology became possible. In the literature, the cold forming of different types of steels [11, 12, 13] was studied by using such software. For instance, Orhan and his colleagues used FEM to produce digital twins of the plastic deformation process. They successfully observed the effect of process parameters on the mechanical properties of AISI 1010 steel [14]. In another study, a different FE simulation software is used to observe residual stress after repair welding in SUS 304 [15]. Li and his colleagues studied the thermomechanical processing of cold forging steel using the CCT diagram with computational materials engineering [16]. In the end, a multiphase microstructure (polygonal ferrite, dispersed pearlite, granular bainite and retained austenite) was obtained. In addition to these studies, commercial FEM software Forge® NxT 3.2, developed by TRANSVALOR S.A, was used to model various cold forming operations [17, 18, 19]. However, little effort has been paid to analysing 27MnB4 steel with computational methods. Thus, there is a need in the literature for a detailed investigation of the cold forging of 27MnB4 steel utilizing simulation software since it has a wide application area in the fastener industry.

The current study focuses on examining the effect of two different annealing types (soft annealing and spheroidization) on the cold forging of 27MnB4 via Thermo-Calc and FEM analysis by comparing with a hot rolled specimen with no additional processing. This work aims to create a correlation between cold forging of 27MnB4 in two different heat treatment conditions and resulting properties such as temperature, stress and strain distribution.

2. MATERIAL AND METHOD

The material used in the present study was 27MnB4 steel, and its chemical composition is given in Table 1. To predict the resulting phases and microstructure after the cooling regime after the hot rolling on the conveyor belt, Critical Transformation Temperatures (CTT) and Continuous Cooling Transformation (CCT) diagrams were calculated according to the given chemical composition by using Thermo-Calc software 2022a TCFE12 (thermodynamic) and MOBFE6 (thermokinetic) database.

Table 1. Chemical composition of the 27MnB4 steel (wt.%).

C	Si	Mn	P	S	Cr	Al	B	Sn	Fe
0.28	0.10	1.00	0.007	0.003	0.26	0.035	0.004	0.006	Balance

Nine wire rod specimens with three different processing conditions (hot rolled, soft-annealed, and spheroidized) were taken from the production line at Kroman Steel Industry. Every specimen was subjected to approximately 300 seconds of controlled cooling on the conveyor belt. Hot rolled samples were prepared for the optical microscopy examinations by grinding with sanding paper 320 to 4000 grit and polishing with a diamond suspension with 3 and 1 μm particle sizes. Samples were etched for 5 to 10 seconds with Nital's reagent to reveal microstructural characteristics. Tensile tests of the specimens under three different conditions were performed according to EN ISO 6892-1 standard. The testing speed for all the specimens was 200 mm/min. Three wire rod specimens of 14 mm diameter were taken directly from the production line. The other six specimens having the same diameter underwent softening and spheroidization annealing heat treatments. The mean value of 3 specimens for each condition was accepted as the yield strength. Yield strength values of hot rolled, soft-annealed, and spheroidized samples were 437, 302 and 255 MPa, respectively.

In this work, as seen in Figure 1, FEM analysis of the cold forming simulation of the bolts contains three stages and the stages represent the upsetting (1st station), head forming (2nd station) and final forming (3rd station), respectively. Every single stage has different upper and lower moulds for cold forging. The billet used in the 1st station is transferred directly to the 2nd station. In the cold forging simulation process, a mechanical press was used with a speed of 60 rpm. Material cards defined in the software were generated by entering experimentally obtained yield strength values for the wire rod specimens in three different conditions.

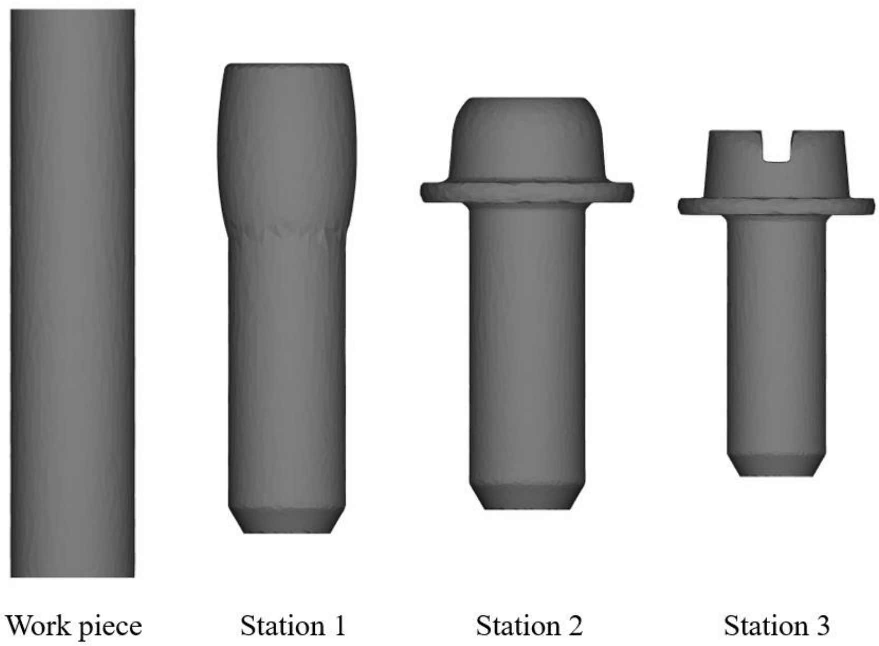


Figure 1. Cold forging of the bolt at three different stations.

3. RESULTS AND DISCUSSION

In the first stage of the current study, functional diagrams that help design the process were presented and interpreted. Phase fractions as a function of temperature were calculated for 27MnB4 steel, as shown in Figure 2. 27MnB4 steel begins to solidify at 1506°C, and the first solidified phase is delta ferrite. At 1489°C, the delta ferrite (BCC) and liquid phase transform into austenite via peritectic reaction. Mn and S elements in steel form MnS intermetallic at 1477°C. Solidification is fully completed at 1441°C. In hypo-eutectoid steels, initially, the pro-eutectoid ferrite (BCC) phase is formed from the austenite (FCC) phase. The point at which pro-eutectoid ferrite begins to form defines the A3 temperature. A3 temperature was calculated as 795°C for the 27MnB4 steel. The eutectoid reaction point at 723°C for the pure Fe-M_3C system transforms into a eutectoid reaction area in multiphase systems. And in that regard, A1e and A1b temperatures were calculated as 732 and 705°C, respectively.

CCT (Continuous Cooling Transformation) diagram was calculated for 27MnB4 steel as shown in Figure 3 by entering grain size as ASTM 8 (25 µm). The hot rolled wire rod temperature was assumed as the austenitization temperature while constructing the CCT diagram, which was selected as 890°C. A1 and A3 temperatures were calculated as 717 and 795°C for 27MnB4 steel, respectively. In addition, Bs (bainite start), M_s (martensite start), M50 (%50 martensite), and M_f (martensite finish) temperatures were calculated as 603, 376, 342, 263°C, respectively.

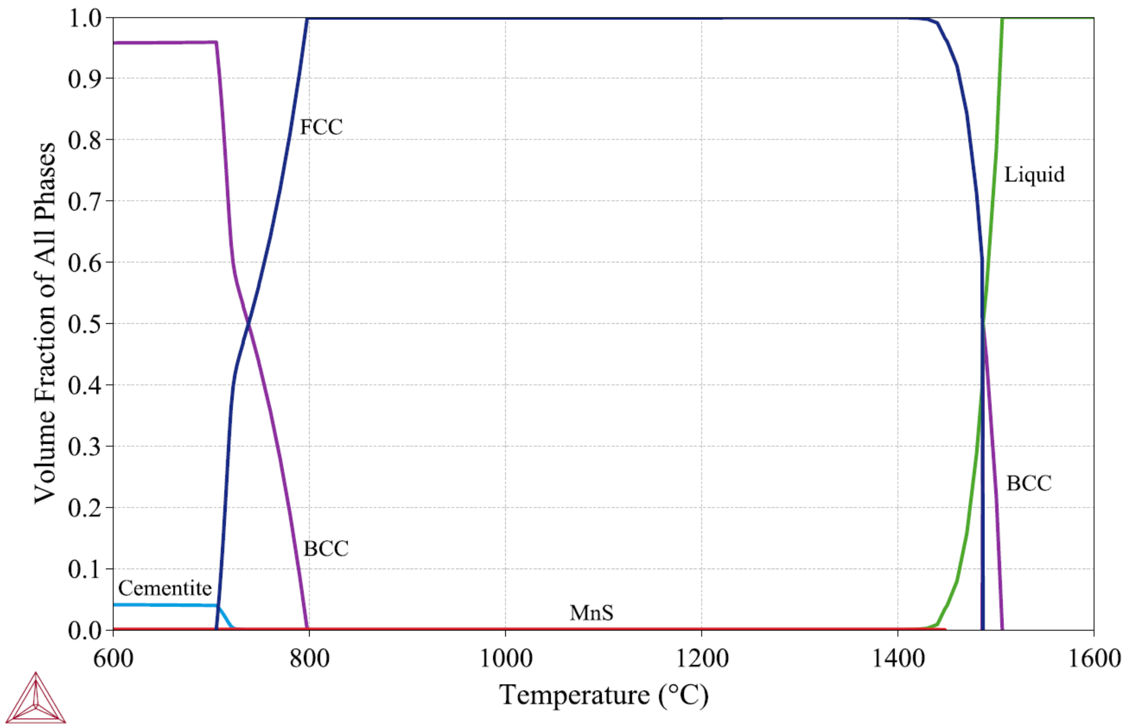


Figure 2. Phase fractions of 27MnB4 steel as a function of temperature.

As mentioned earlier, the calculated CCT diagram was used to predict the microstructure of the cooled specimens for approximately 300 seconds after the hot rolling station. According to the CCT diagram, the resulting microstructure after the controlled cooling consists of ferrite and pearlite/bainite (a mixture of ferrite and carbon-rich cementite). As seen from the optical microscopy image in Figure 4, the evolved microstructure is mainly a mixture of ferrite and pearlite/bainite. Lighter areas are defined as pro-eutectoid ferrite, the first phase to form from austenite solid solution upon cooling. Darker areas are pearlite/bainite mixture that can be both lamellar and acicular depending on the different cooling rates. In low/medium carbon steels containing manganese, it is hard to distinguish ferrite/carbide aggregates precisely using optical microscope techniques since the morphology of these aggregates (lamellar or lath structure) can't be determined. Hybrid microstructures with ferrite, pearlite, and bainite can be formed due to controlled cooling [20, 21]. Therefore, it can be stated that the calculated CCT diagram provided an accurate estimation of the final microstructure for hot rolled specimens.

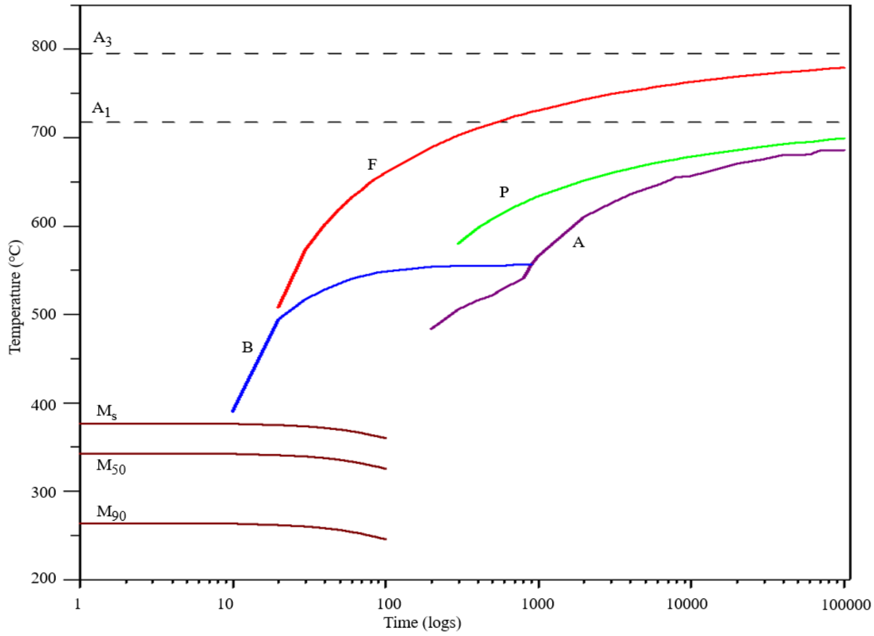


Figure 3. CCT diagram of 27MnB4 steel.

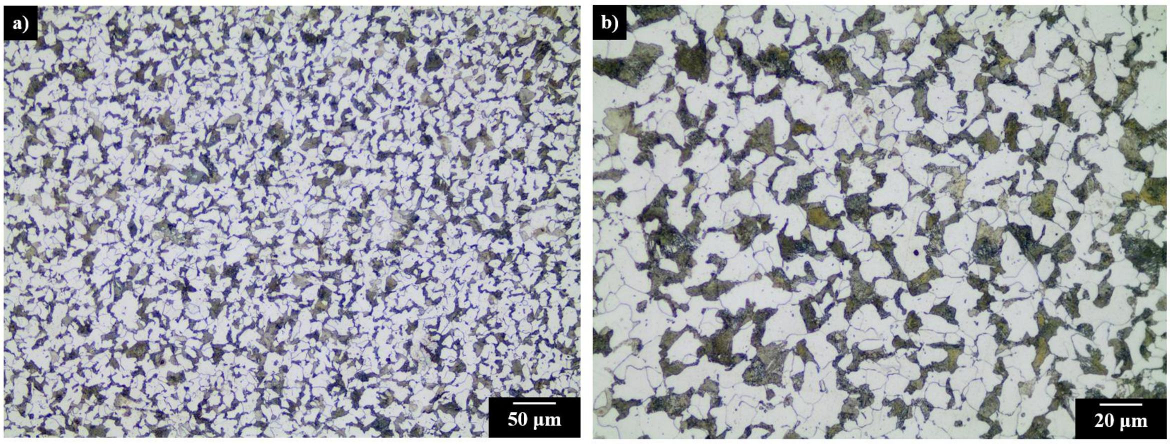
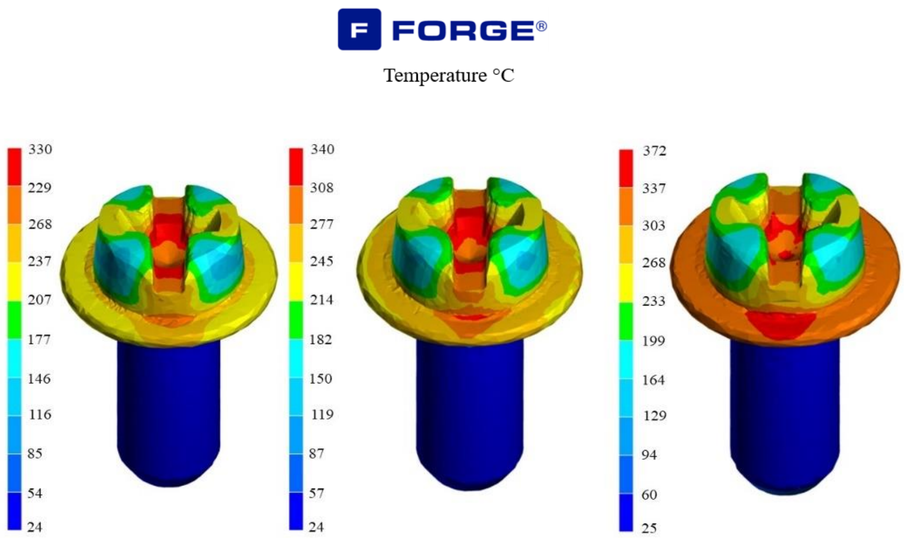


Figure 4. Microstructure images of hot rolled 27MnB4 wire rod at different magnifications a) 50X and b) 125X.

The second stage of the current study aims to examine the effect of microstructure (spheroidized/soft annealed) on the cold formability of 27MnB4 steel and compare it with the hot rolled sample. Simulations of bolt forming for the 27MnB4 steel were performed, and temperature, von Mises stress, and equivalent strain distribution were investigated. Regarding the temperature distribution of the 27MnB4 alloy through simulation, it was observed that the hot rolled condition exhibited a higher temperature evolution for all the stations than the soft annealed and spheroidized conditions. In the last station of the 27MnB4 fastener forging, the maximum temperature obtained for the hot rolled condition was 372°C, for the soft annealed condition 339°C, and for the spheroidized condition was 329°C. The main reason for the temperature difference as shown in Figure 5 is the need for higher energy to deform materials with higher yield stress due to resistance to yielding. Figure 6 and 7 represents the distribution of von Mises stresses for different stations with two different views. Since the bolt geometries do not differ for the three conditions, stress-concentrated areas were identical. The overall distribution of von Mises stresses for hot rolled 27MnB4 steel is higher than the annealed (spheroidized/soft) samples. This issue can be explained by the microstructural differences induced by the heat treatment process. Applied sub-critical heat treatment transforms the lamellar cementite into spheroidal form and the final microstructure has a lower yield point which facilities the cold forming process [22, 23]. As a result, stress evolution during the forming process decreases and failures such as splits can be avoided [18]. In addition, the stress distribution also represents the residual stresses after manufacturing. For the spheroidized condition, residual stresses at the highly deformed parts are lower than in soft annealed and hot rolled states. In addition to von Mises distribution, the distribution of equivalent strains was investigated. Figure 8 represents the distribution of equivalent strain for the final station. The mean value of equivalent strains for hot rolled 27MnB4 steel is slightly higher than annealed steel for the final station. This strain distribution difference can be explained with a microstructural difference, as in the case of von Mises distribution. The presence of spheroidal cementite lamellae in pearlite for annealed samples enhances the formability compared to the hot rolled sample. Thus, it is possible to observe slight differences in the equivalent strain distribution between two different microstructures. In addition, as the fastener undergoes plastic deformation, strain hardening occurs. As shown in Figure 8, high-strain regions exhibit higher stresses due to the strain-hardening effect.



a) b) c)

Figure 5. Temperature distribution of 27MnB4 steel for a) spheroidization, b) softening annealing, and c) hot rolled condition.

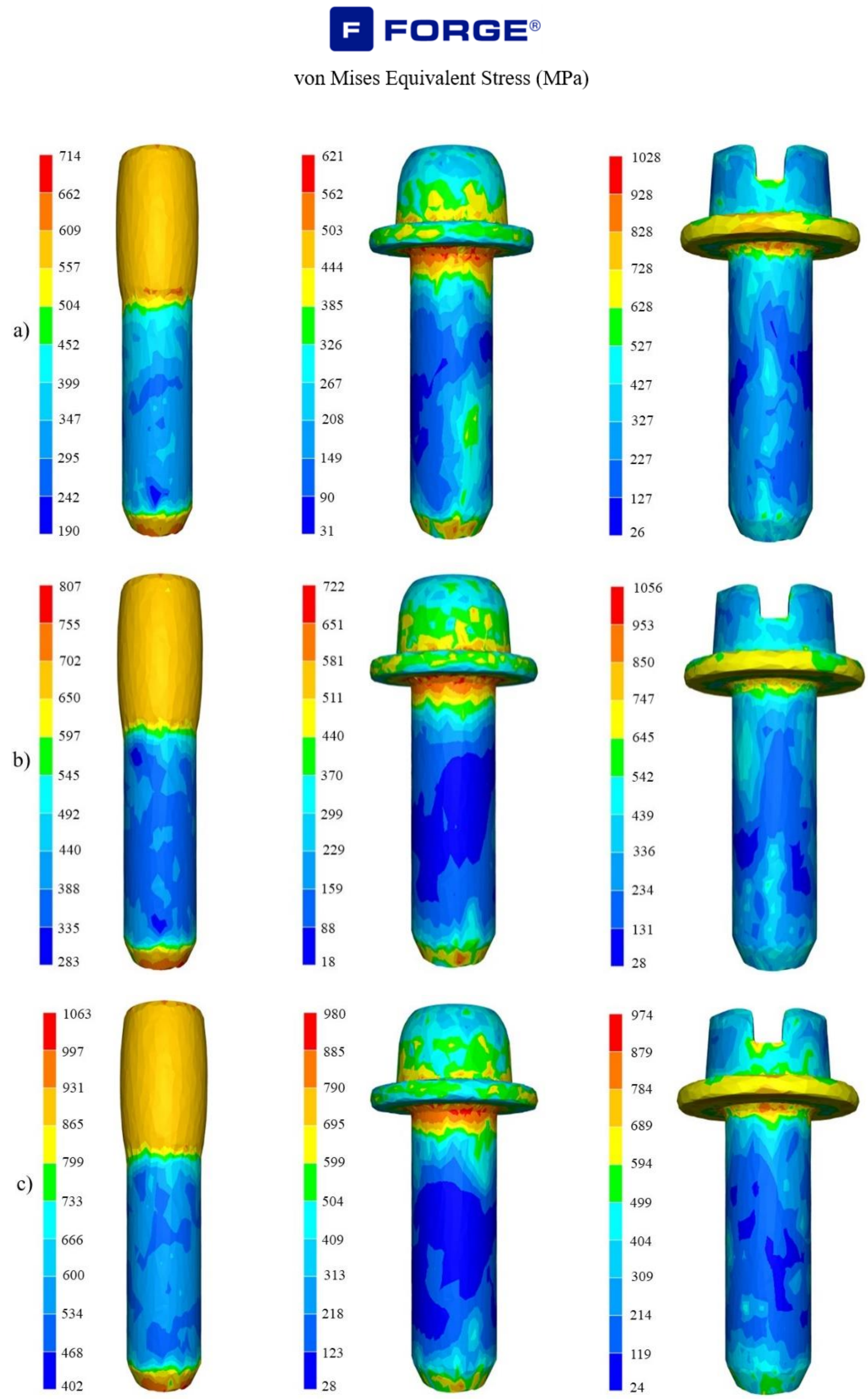


Figure 6. Von Mises stress distribution of 27MnB4 steel a) spheroidization b) softening annealing c) hot rolled condition (side view).

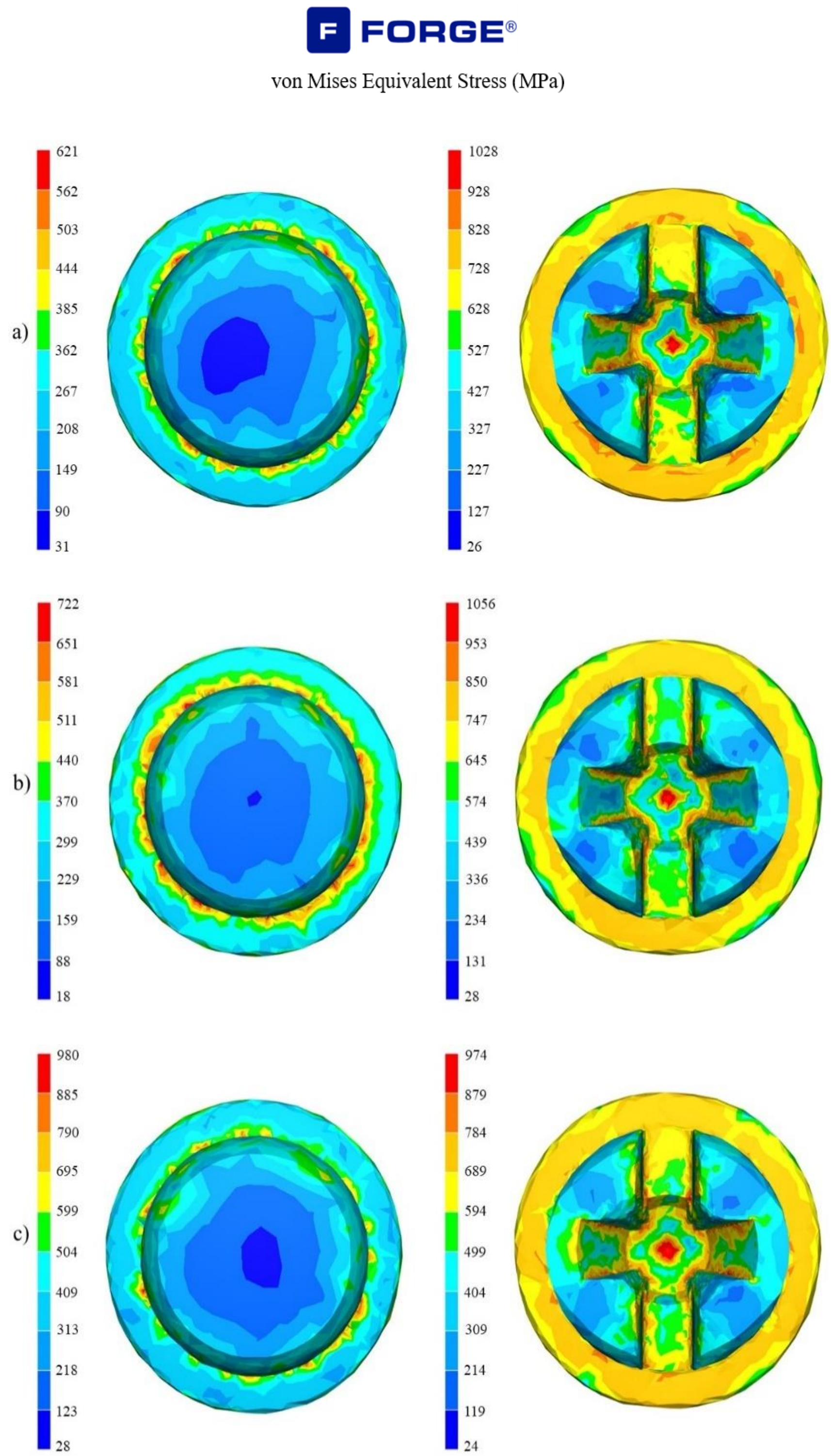


Figure 7. Von Mises stress distribution of 27MnB4 steel a) spheroidization b) softening annealing c) hot rolled condition (top view).

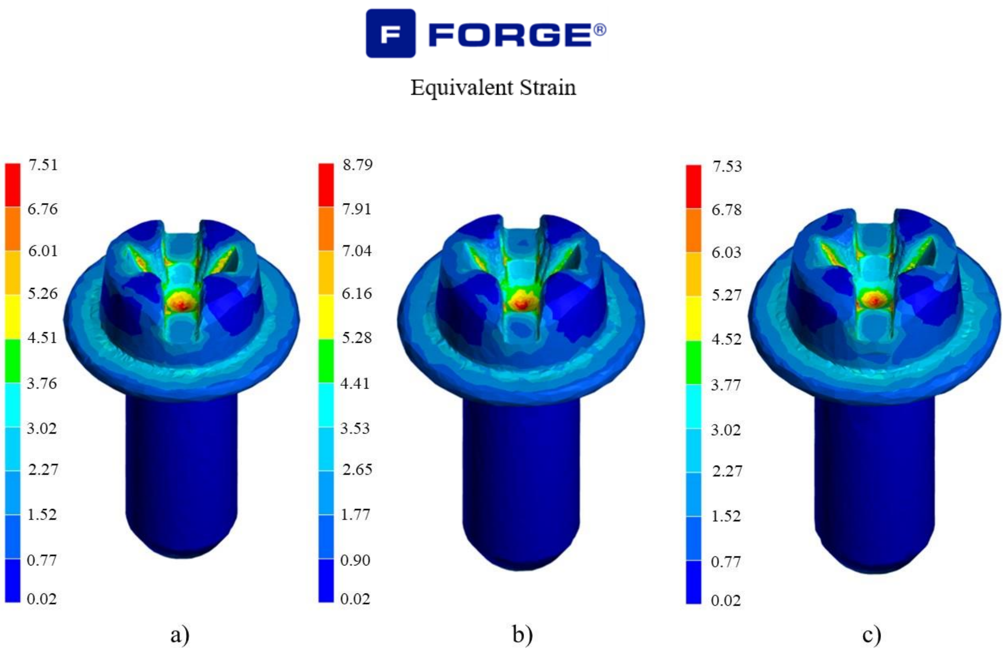


Figure 8. Equivalent strain distribution of 27MnB4 steel for a) spheroidization, b) softening annealing, and c) hot rolled condition.

In the literature, there are not many studies available about bolts or fasteners produced with 27MnB4 steel. In bolt production, the change of any process parameter in the forging step or the change of the chemical composition in the production material can directly affect the outcome. For this reason, the same material and the same production conditions should be used for comparison. In this work, similar studies from the literature were examined. Also, different production conditions and different material conditions were taken into consideration.

The cold forging process of 51B40 steel was modelled with Forge NxT software [17]. According to this study, the equivalent strain value was found to be a maximum of 3.76 in the region where the yield strength is exceeded. When compared with this study, it is similar to the value obtained as a result of the upsetting process obtained in 2nd station.

The fastener cold forging process was modelled for automotive batteries with Deform 3D software [24]. The process is designed as five stages. In the 5th stage of the process, the effective stress distribution was quite homogeneous. However, it can be said that the stress differences exhibit similar behaviour with this work, and it also increases proportionally with temperature.

In another work, forging simulation was modelled with Autodesk Inventor CAD software [25]. There were three forging stages similar to our study. In 2nd stage, the maximum effective stress of 758 MPa was observed when the upsetting process was completed. In addition, this effective stress was formed from the lower part of the upsetting process. When compared with our study, the homogeneity of the effective stress distribution with the von Mises stress distribution is similar. In addition, as seen in Figure 6, our von Mises distributions are such that they are maximum below the upsetting part.

From an originality view, this is a novel study due to the material, simulation selection and outcomes. Combining computational materials engineering with FEM is essential and needed for fastener fabrication. Especially in recent years, less energy consumption, and the use of more sustainable materials within the scope of environmentalism and sustainability become more and more essential for a better future. In this context, computational materials engineering and FEM will provide energy, economy and labour savings while performing R&D studies and serial production verifications for fastener production.

4. CONCLUSIONS

In this work, the effect of annealing treatment on the cold forging process of 27MnB4 bolts via FEM analysis was investigated. Results from the present study can be summarized as follows:

- CCT and CTT diagrams were used extensively in this study. CCTs and CTT diagrams significantly influence the final product microstructure development and resulting properties. Critical parameters such as rolling temperature and cooling regimes can be determined via CCTs and CTT diagrams, leading to optimum processing conditions and manufacturing of steel bolts with the desired properties.
- The differences in the microstructure affect the cold forging capability of the 27MnB4 steel. In the annealing treatment, the cementite lamellae in pearlite/bainite will spheroidize, creating small and round cementite particles in the ferritic matrix to improve formability. Thus, the microstructural difference affects the distribution of stresses and strains of 27MnB4 steel.
- The distribution of temperature, von Mises stress, and equivalent strain for 27MnB4 steel in the hot rolled state was higher than in annealed states due to the differences in the microstructure.
- The focus of the current study was to examine the effect of two different annealing treatments on the cold forging process of 27MnB4 bolts via two commercial CALPHAD and FEM-based software: Thermo-Calc and Forge® NxT. This study aims to fill the gap in the literature by creating a correlation between the cold formability of 27MnB4 and resulting properties such as temperature, stress, and strain distribution.

Declaration of Ethical Standards

All authors in the study followed all ethical guidelines, including authorship, citation, data reporting, and original research publication. The authors contributed equally to the article.

Credit Authorship Contribution Statement

Yagiz Akyildiz: Conceptualization, Writing – original draft – review & editing, Software, Investigation, Supervision. **Umit Kutsal:** Writing – original draft – review & editing, Visualization, Software, Investigation. **Yagiz Arslan:** Writing – original draft – review & editing, Visualization, Software, Investigation. **Adnan Akman:** Writing – original draft – review & editing, Visualization, Software, Investigation. **Atif Karkinli**: Writing – original draft – review & editing, Visualization, Software, Investigation. **Mert Saglam:** Writing – original draft – review & editing, Visualization, Software, Investigation. **Ridvan Yamanoglu:** Supervision, Writing – review & editing, Conceptualization, Investigation.

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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Data Availability

The data that has been used is confidential.

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