J. Min. Metall. Sect. B-Metall. 59 (2) (2023) 299 - 314

Journal of Mining and Metallurgy,
Section B: Metallurgy

EFFECT OF FORGING SEQUENCE AND HEAT TREATMENT ON MICROSTRUCTURE OF HIGH-DUTY POWER-PLANT SHAFT MADE OF Cr-Mo ULTRA-HIGH STRENGTH STEEL

P. Skubisz*, **Ł. Lisiecki**

AGH University of Science and Technology, Faculty of Metals Engineering and Industrial Computer Science, Cracow, Poland

(Received 05 October 2022; Accepted 27 August 2023)

Abstract

The paper presents the results of modeling and testing of a heavy weight part made of Cr-Mo, which was V-modified ultra-high strength steel grade AISI 4140, processed through a novel open-die forging program and two alternative routes of two-stage heat treatment cycles designed to meet requirements of high-duty components for energy sector. By using unconventional forging conditions based on the assumption of large feed and reduction ratio and modifying the chemical composition, better control of the austenite grain was achieved to minimize abnormal grain growth and/or strain uniformity problems. Using the Finite Element Modeling, the multi-stage sequence of upsetting and the cogging strain distribution were optimized to minimize the strain variation along the length to a range 2.2÷2.7, and correlated with the microstructure generated at each main stage on the large cross-sections of the shaft. Mechanical and thermal processing cycles designed using the finite element method were fully verified physical modeling using a 16 ton forging block, including two alternative quenching strategies: oil vs. water spray and air. The material was studied in the as-forged, normalized and heat-treated states to observe the behavior of the hot-formed material and the effects of cooling conditions on the microstructure during the final heat treatment. It was found that the use of large feed ratios on cogging and varied cooling allowed to suppress the adverse effects of the inevitable abnormal grain growth, resulting in 1–2 ASTM in forged condition and reaching 6 ASTM and 8/9 ASTM after quenching in oil and water spray, respectively, which allowed a corresponding notched impact strength of 44÷48 and 85÷122 J/cm^2 in the critical region of the forged shaft after tempering.

Keywords: *Hot forging; Power-plant forged shaft; Cr-Mo high-strength steel AISI 4140; Cogging; Open-die forging; Abnormal grain growth*

1. Introduction

Improvement of performance and reliability of power-plant components with minimization of maintenance of renewable energy sources is one of the most significant concerns in civil engineering nowadays. Notwithstanding quality requirements may draw severe economical and/or environmental losses. Possible costs of compensation for failures to uphold continuity of electricity supply serves as the chief impetus behind the ongoing drive to develop materials and processing methodologies tailored for high-duty parts destined for energy applications [1-3].

For applications demanding elevated performance, where superior performance and operational reliability is required Cr-Mo alloyed steels emerge as the natural contenders. Among these, ultra-high strength steel (UHSS) grade 42CrMo4 (AISI 4140) is one of the most representative, presenting a well-balanced array of mechanical properties, offering moderate-to-high mechanical properties (e.g. available for heavy weight components after the conventional heat treatment (quenching and medium or high tempering) for martensite-bainite microstructure which is highly suitable for applications involving heavy sections [4-7]. As such, it finds a wide range of applications in aircrafts, power-plant and/or petroleum industry high-duty parts, expected to bear high thermal and mechanical cycling loading of variable sign and direction [8, 9], for instance in manufacturing of generator shafts and/or turbines. Because of the high moments they are expected to transfer in wind-mill transmission systems, and their large size, parts like these are manufactured by means of open-die forging, which is non-competitive technology for producing heavy parts combining strength and ductility.

Although steel AISI 4140 has been successfully used for high-duty rolled and/or die-forged products and the effect of processing conditions on its properties and microstructure has been extensively studied [6, 10-

Corresponding author: pskubisz@agh.edu.pl

https://doi.org/10.2298/JMMB221005026S

12], the intricate dynamics linking technology, microstructure, and properties in hefty components meticulously designed to meet exacting safety requirements for high-duty applications seem to be somewhat understudied. Among the most responsible wrought parts made of this steel are components for power plant transmission systems. In addition to shape and dimensional tolerances, the forging process is meant to eliminate defects in the ingot of metallurgical origin, breaking up coarse-grained dendritic structures and non-metallic inclusions and affects the form of carbides [13-15]. Therefore, forged heavy parts are produced through intense plastic working aimed at breaking down ingot structure [16] and metallurgical structure restoration for grain refinement and, if conditions are fulfilled to avoid oxidation, partial eradication of internal discontinuities [17-20]. Closing internal discontinuities during forging stages prevent them from nucleation of cracks which might originate defects during secondary open-die hot forging steps or, which worse, can go undetected until heat treatment open or in service [21, 22].

From the quality and performance standpoint, forging conditions are of crucial significance. Whereas accomplishment of geometry as close as possible to final dimensions is an economy concern, plastic work of the material results in improvement of workability, metallurgical soundness and superior mechanical properties at the same time [23]. Thus, forging stage brings about indispensable preparation of the worked material for subsequent heat treating, which provide the forged part with final strength and cracking resistance [24, 25].

In fact, the only method of plastic working of heavy parts is open-die forging – discontinuous sequence of multiple strokes expected to produce the minimum of required amount of strain in as uniform as possible both longitudinal and transverse distribution so as to produce homogenous microstructure and prevent from the occurrence of abnormal grain growth [26, 27]. In forging practice, of most significance here is overcoming the inherited macrostructural inhomogeneity and natural for cogging non-uniformity of plastic deformation, which is inevitable result of discontinuous sequence of unit strokes interacting with one another. The local maxima – resulting from superposing consecutive strains, and/or strain minima – resulting from inadequate strain or feed ratio [28, 29]. Key issue is making the deformation zone penetrate the axis region, which is crucial from the standpoint of presence of imperfections. Thus, to meet the high requirements for mechanical properties it is necessary to control the process parameters in every step of the technological chain. Therefore, it is obligatory to conduct the process with proper feed ratio and unit reductions – both controlled by available load. Considering decreasing temperature adversely affecting forgeability in inconvenient state of stress, typical of open-die forging, which makes this process a hard-to-design cycle. While numerical simulation codes form an effective aid in selection of favorable combination of process parameters [30-33], implementation of the virtually formulated guidelines is not always easy or possible in forging practice as in case of large diameters excessive load is needed, which restricts the use of large feed and reduction ratios. Then intermediate values used as compromise promote abnormal grain growth [34-35] effects of which are inherited in microstructure of heat treated product and are hard to heal. The presented work shows the effect of modification of chemical composition and processing schedule of high-strength steel AISI 4140 after deformation sequence optimized for high-productivity and more extensive deformation zone for two alternative routes of two-stage quenching on strain distribution and microstructure before and after heat treatment.

Thus, the motivation of the study grows out of the vital need for increasing the safety and performance of crucial components to meet the expectations of power industry dictated by the tendency to higher loading of the structural components, as well as social needs and ecology aims, by increasing efficiency of traditional technologies and reduction of energy and media. The presented work investigates the possibility to overcome limitations of traditional approach to use knowledge and modern design tools to propose technology based on the most effective use of available strengthening mechanisms at reduced time and resources. The culmination of this study underscores the verified application of stringent forging parameters and meticulously tailored heat treatment schedules. These methodologies are examined with a keen focus on their influence on the ultimate microstructure of the specially designed high-duty power-plant heavy forgings. The findings underscore the potential to achieve finely tuned microstructures in the context of heavy forged shafts.

2. Materials and methods

2.1. Goal of the study

The goal of the study is an investigation of the effect of large feed ratio (during cogging sequence) and of subsequent heat treatment on microstructure and selected mechanical properties of a heavy shaft formed shaped in open-die forging sequence, taking advantage of modified chemical composition of UHSS AISI 4140, verifying thereby the possibility of its industrial realization and indicating cooling cycle to provide required microstructure.

The experimental part consists of numerical and physical modeling of complex multistage open-die forging process in industrial conditions of massive forged shaft made of steel AISI 4140, followed by heat treating. The flowchart of the research tasks, with flow of the results is shown in Fig. 1. Starting from the geometry and material considerations of the reference process, parameters for simulation of forging and target property-microstructure requirements are selected. In modeling of material behavior and transformations on cooling so as to predict product of austenite overcooling and potential precipitates for control of microstructure initial data for simulation are achieved. The numerical modeling with finite element method (FEM) allows the design of the technology, and correlation process parameters with strain and temperature fields, which are inherited further in heat treatment (HT) simulation. Conjunction of FEM modeling of HT and calculated in TTSteel software CCT diagrams allows prediction of volume fractions of structural constituents after alternative cycles for consideration, whereas, modeling in Factsage illustrates precipitation products resulting from V microalloying. This altogether forms a basis for experimental test of forging and cooling.

The forging test considered is representative of a typical process of manufacturing heavy high-duty forged shafts, comprising of upsetting and cogging free-forge operations. The study was aimed at representation of industrial sequence of forging and heat treating operations, oriented at investigation of the effect of modified forging sequence with an intent to reduce detrimental impact of strain inhomogeneity on

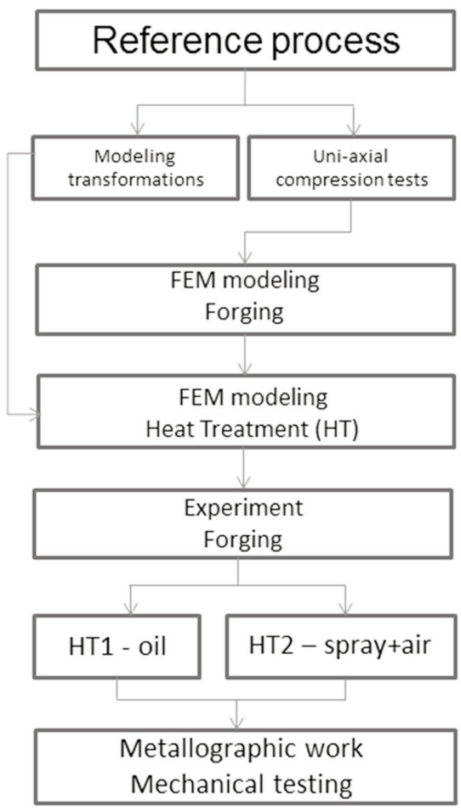

Figure 1. *Flowchart of the research plan*

microstructure evolution and designing a heat treating schedule proper for desired structural constituents profile after quenching-tempering (QT) heat treatment.

The research method is based on full-scale physical modeling of forging and heat treatment, aided with numerical simulation of forging sequences to illustrate plastic work history and to define the total amount of deformation produced within the whole forging chain to provide specimens for microstructure analysis in as-forged, normalized and quenched-tempered condition. As-forged and heat-treated microstructure suggests to what extent the modifications in chemical composition in combination with rigorous yet economically beneficial forging schedule helps to eradicate detrimental effect of abnormal grain growth.

Because the V additions are proven to act during cooling all the way from forging run-out, annealing [36, 37] to the final heat treatment, fostering microstructure-properties combination, mainly through grain refinement and structural constituents after heat-treated microstructure by e.g. affecting hardenability [38] or strain effect on CCT curves [39-41], the concluding statements on the effect of the modified steel composition and process conditions can only be formulated with consideration of all processing stages, including final heat treatment. As the above described changes rely on V-modified chemical composition, it is no use make comparative analysis the results of implementation of proposed process modifications to traditional process.

2.2. Material

Chemical composition of the modified alloy is shown in Table 1. The modified composition was based on AISI 4140 commercial grade modified by addition of grain controlling microalloying element and slightly increased silicon content in order to improve cracking resistance and grain controllability.

Continuous cooling diagram for this heat were established in TTSteel code. Experimental heat the experimental steel was cast into 16 Mg traditional ingot.

After homogenizing, annealing ingot had undergone plastic work in upsetting and cogging open-die forging operations to break down as-cast structure and refine primary grain structure. For possibly high efficiency of plastic working of the material, expected to bring about uniformity of strain in the bulk, high feed ratio and unit reductions were imposed while open-die forging operations. Having received proper amount of plastic deformation, equivalent to effective strain over 2.5 in the core zone and over 5 in the undersurface areas, the material was subject to two-steps heat treatment, including preliminary heat treatment aimed at refinement of as-forged grain structure (Fig. 2) and after subsequent rough machining, final heat treatment

Table 1. *Chemical composition of the modified steel AISI 4140 used in the study*

Element	C	Mn	Si	Cr	Mo	Ni	S	P	V	Fe
Content, wt. %	0.42	0.83	0.28	1.14	0.32	0.3	0.003	0.008	0.006	Bal.

described later on. After each of the crucial stages of investigation specimens were extracted for microstructure analysis (as shown in Fig. 3). The microstructure analysis involved examination of material in as-forged, normalized and heat-treated condition was carried out for analysis of microstructure quality obtained with modification of chemical composition. The effect of deformation and heat treatment conditions realized in accordance with the cooling simulations, on the evolution of microstructure was investigated through analysis of specimens in as-forged, normalized and heat-treated condition. For quantitative evaluation of the grain size dependence on the forging-cooling conditions comparison method in accordance with ASTM E112-10 was applied with reference to former austenite reveled by the method of outlining the grains with ferrite, as well as estimation of volume fraction of phases. In addition to microstructure, V-notch impact energy was measured on 300J Charpy device.

2.3. Modeling of the forging sequence

The calculations of forging technological chain investigated involved a multi-stage sequence of forging operations reflecting experimental forging procedure (Fig. 4). Thus, complete history of deformation and temperature was attained in the analysis.

The forging sequence was carried out on a hydraulic press of 80 MN capacity and working speed of about 20 mm/s. The work material in a form of large ingot weighing 16 Mg (Fig. 4a) was heated up in a gas furnace and soaked to obtain uniform 1250 °C start forging temperature, with a 650 °C hold for equalization of temperature and thermally-isolated in thermos it was transferred to the press table, where the manipulating boss was formed (Fig. 4b). The first step was upsetting of the ingot (Fig. 4c) to enable higher cross-section reduction ratio, and thereby, larger amount of strain during subsequent cogging in flat narrow dies. There, the diameter of the preformed ingot was reduced to 630 mm (Fig. 4d) in multiple cogging passes (Fig. 5), realized with a use of unconventionally large feed ratio (0.7), defined as deformed length to diameter ratio. Significant height reduction ratio 0.4-0.5, in combination with high feed ratio, was meant to produce strain distribution more uniform than conventional 0.5÷0.6 values and more efficient breakdown of the ingot structure.

According to the predictions provided by FEM analysis, starting from 3 feed lengths (bites) in the

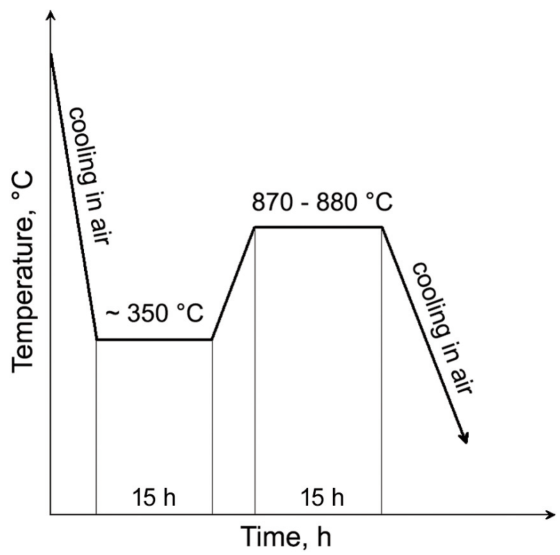

Figure 2. *Schedule of preliminary heat treatment*

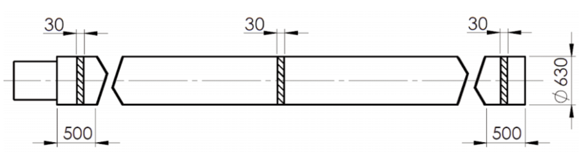

Figure 3. *Location of specimens extracted for metallographic examination and Charpy tests*

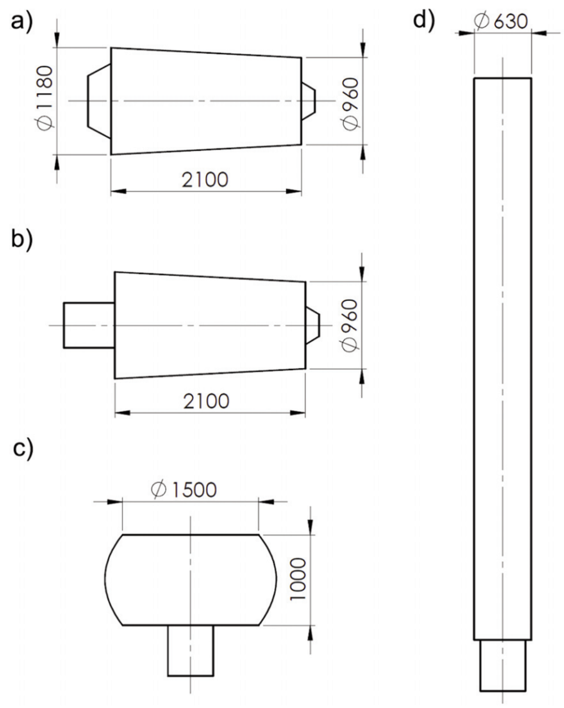

Figure 4. *Dimensions of forged shaft after consecutive forging operations used in experiment: a) initial dimensions of 16 Mg ingot, b) shaping a manipulating boss, c) upsetting, d) cogging*

first pass (flattening the ingot on one plane), every next pass, coming after rotation by 90 degrees around shaft's axis, involved a bite more. Having reached required length and cross-section, smoothing passes aimed at braking edges proceeded, forming octagonal cross-section (Fig. 5 f-g), which in forging practice are followed by a number of smaller smoothing strokes; with little effect on properties and, as a rule, neglected in theoretical analysis. The process of cogging, contrary to incremental forming processes, is discontinuous and yields more or less nonuniform distribution of amount of strain on the length. The higher feed ratio, the more uniform the strain pattern. However, increasing feed length cause forging load rise, which limits the bites' length, in addition to anvil geometry. The FEM analysis is oriented on estimation of the effect of the use of larger-than-usual feed ratio on strain indices, e.g. effective strain, and indication of potential overloading or need of reheating.

In FEM modeling of the forging process three-dimensional state of strain was used, with assumption of rigid-viscoplastic model of a deformed body and Levanov friction model, assuming friction factor 0.4 and friction coefficient 0.3. Rheological characteristics of the analyzed heat of the modified steel grade for the purpose of numerical simulation of forging (Fig. 6) was derived from uni-axial compression tests carried out on Gleeble 3800 testing machine for temperature range 1200÷800°C, covering expected forging regime of the analysed steel, and strain rates 0,01÷100 s^{-1}. After inverse method correction, they were used for estimation of coefficients of Hensel-Spittel equation (1), listed in Tab. 2, which extends range of process parameters of available literature data [16, 42].

Numerical calculations were performed for forging sequence, temperature regime and values of unit reductions and feed ratio reproducing experimental procedure. In accordance with process parameters typical of industrial forging conditions, initial temperature of forging 1220 °C, tool temperature 300 °C and temperature-dependent emissivity coefficient 0.86 to 0.62 [43] were assumed.

$$\sigma_P = A e^{m_1 T} T^{m_9} \varepsilon^{m_2} e^{m_4/\varepsilon} \left(1+\varepsilon\right)^{m_5 T} e^{m_7 \varepsilon} \bar{\varepsilon}^{m_3} \bar{\varepsilon}^{m_8 T} \tag{1}$$

For estimation of amount of deformation equivalent strain (effective strain) ε_H was used:

$$\varepsilon_H = \frac{2}{\sqrt{3}} \sqrt{\left(\varepsilon_x - \varepsilon_y\right)^2 + \left(\varepsilon_y - \varepsilon_z\right)^2 + \left(\varepsilon_z - \varepsilon_x\right)^2 + 6\left(\varepsilon_{xy}{}^2 + \varepsilon_{yz}{}^2 + \varepsilon_{xz}{}^2\right)} \tag{2}$$

where indices x, y, and z stand for the main directions.

Besides forging load and temperature, effective strain was calculated with finite element method (FEM) with use of a commercial code QForm3D, which proved reliable in modeling of multistage forging processes.

Table 2. *Coefficients of Hensel-Spittel equation assumed in FEM simulation of forging*

Parameter	Value
A	6267.37
m_1	-3.22852e-3
m_2	0.10181
m_3	0.14470
m_4	-1.75479e-2
m_5	2.97323e-5
m_7	-0.14767
m_8	-5.18486e-7
m_9	0.56217

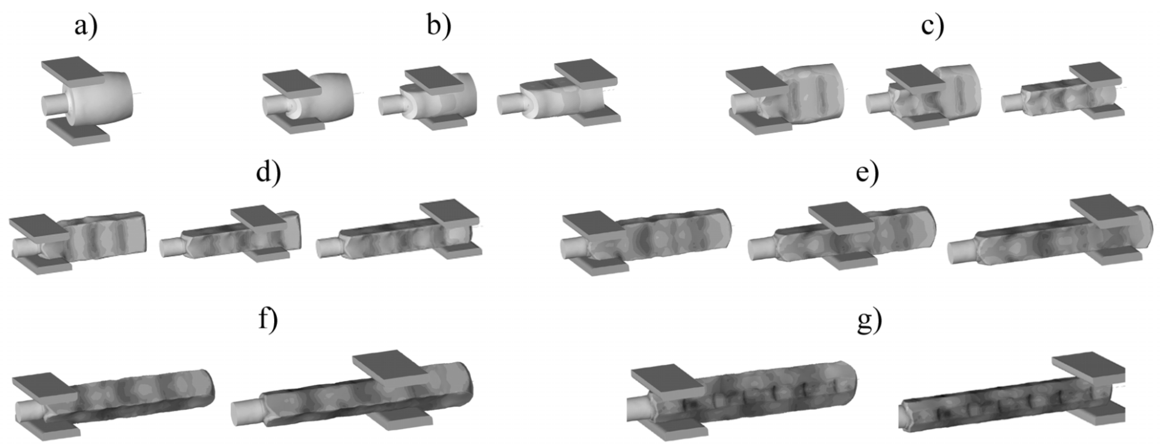

Figure 5. *Shape and strain evolution of the forged shaft obtained from simulation in QForm3D for consecutive stages of forging: a) smoothing, b) upsetting, c) flattening, d-e) cogging through square, f) cogging through hexagon, f) cogging through octagon*

2.4. Modeling of the heat treatment schedules

After the forging operations are complete, the next step in manufacturing chain is a preliminary heat treatment, whose objective is to secure the component against cracking and to obtain proper grain size, followed by the final heat treatment, which determines final strength and ductility properties.

After forging and normalizing annealing in 880 °C, the forged shaft was subject to quality heat treatment (HT). On the basis of CCT diagram austenizing temperature of 860 °C was selected, and it reached intermediate equalizing hold at 650 °C. After sufficient soaking time at austenizing temperature, quenching was carried out with variable cooling rates, corresponding to differing cooling media: 1) oil (Fig. 7a), and 2) air-atomized water and air (Fig. 7b). The experiment was to show the hardenability of as-forged dynamically recrystallized structure and response of as-forged material to imposed cooling conditions. As-quenched material was subject to tempering, both in the same conditions. Tempering regime typical of Cr-Mo grades oriented at attaining high strength, omitting the ranges of irreversible temper embrittlement [44]. Simultaneously, former austenite grain produced in the aftermath of deformation and static recrystallization was revealed, making it possible to evaluate microstructure of as-forged material as the aftermath of modified forging sequence featured by increased feed length.

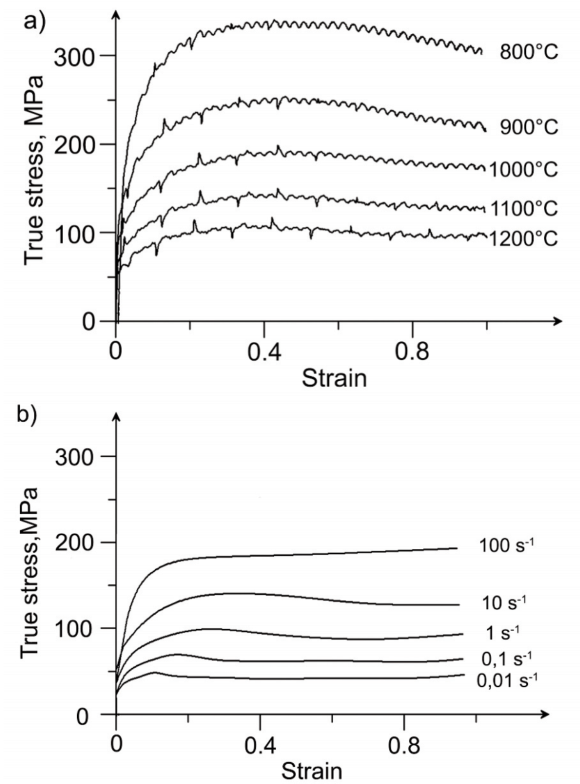

Figure 6. *Selected stress-strain characteristics of steel 42CrMo4 obtained from uni-axial compression tests: a) temperature dependence for constant strain rate 10 s^{-1}, b) strain-rate dependence for constant temperature 1100°C*

For selection of optimal heat treating route (or exclusion of lest beneficial ones) experimental tests were preceded by numerical simulations. HT simulation was carried out in QForm heat treatment module with adaptation of boundary conditions to environment to be applied in real process. In addition to those used in forging simulation, heat transfer coefficient characteristics used in related studies [45, 46] were assumed. Characteristic curves of austenite transformation for metallographically determined grain size were calculated in code TTSteel and further in preliminary prediction and quantitative calculation of fraction of structural components and mechanical properties.

3. Results and discussion

3.1. Numerical estimation of strain

On account of critical significance of strain magnitude in influencing the kinetics of austenite transformations and the subsequent morphology and grain size of their resultant products, the assessment of total effective strain post-forging emerges as a pivotal consideration, especially, if new steels are dealt with.

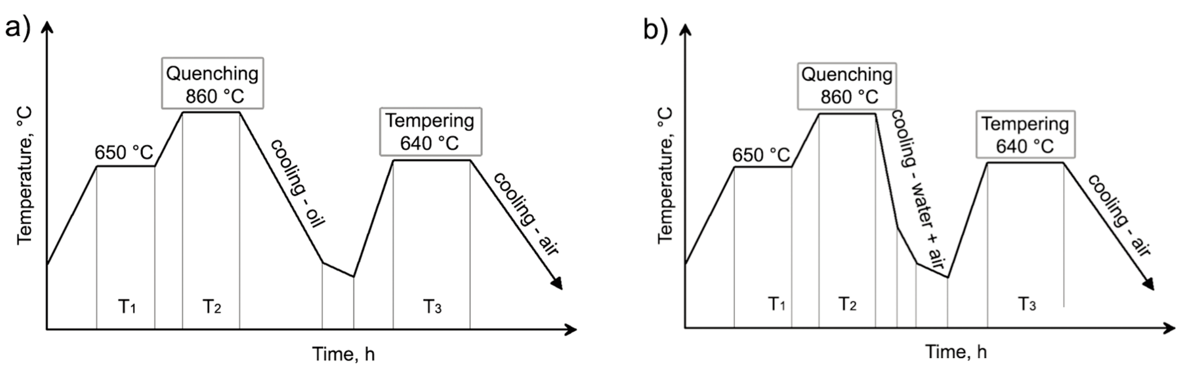

Figure 7. *Heat treatment schedules applied in the experiment while cooling with: a) oil, b) water spray–air sequence*

Thus, considering feasibility of use of large feed ratios, attention was paid to the problem of reaching required level of the total amount of strain and its distribution in the bulk, which is illustrated by a series of maps in Fig. 8 and graph in Fig. 9a). Detailed analysis of amount of strain is enabled by use of numerically estimated effective strain (2). The calculated values of ε_H allows the conclusion of good uniformity of strain in a bulk. Except for the ends of the sample shaft, where value of effective strain observed in the axis decreased to 2.25 (Fig. 8 b, d), effective strain of 2.5 or higher was observed throughout the entire shaft's length (Fig. 8a), which was believed sufficient for breakdown of ingot primary structure with simultaneous closing the internal porosity, including axial zone.

The surface and undersurface regions conspicuously exhibit heightened levels of deformation, giving rise to a finely-grained outer layer. Even with effective strains surpassing 2.5, the peaks of strain generated by the interplay of deformation zones stemming from consecutive passes remain intact (Fig. 8a), which persisted despite employing feed lengths closely aligned with tool lengths, yielding strain fluctuations characteristic of the shaping process involved [19]. It is worth noting that the initial passes contributed to a more pronounced increase in effective strain, whereas subsequent ones tended to mitigate these peaks (Fig. 9a). This particular aspect warranted consideration in the crafting of the forging sequence, and by extension, the anticipated homogeneity in microstructure-property relationships. This showed that the inherent inhomogeneity of strain within the bulk was an inevitable outcome in cogging process, as it appeared while using the most possible feed lengths. Herein, the chosen feed ratio values aligned favorably with both quality and productivity imperatives, provided the press capacity could accommodate the increments in load necessitated by a larger volume subjected to concurrent deformation (stages 2÷7 in Fig. 9b), albeit likely not reaching the point of upsetting (stage 1 in Fig. 9b).

To sum up, the numerical simulation of the forging process attested to the correctness of the devised deformation sequence, particularly in its ability to achieve the requisite minimum strain level, with uniformity across both axial and transverse cross-sections. A quantitative comparison of calculated ε_H versus the length of the shaft, shown in Fig. 9a), confirmed effectiveness of the use of large feed ratio as for accomplishment of the required strain level in a bulk.

As a factor of great importance in design of forging scheme, in addition to strain, temperature development was observed. The information on the distribution of temperature on cross-section (Fig. 10 a, b) formed a background for microstructure prediction, as well as whether or not it was necessary to reheat the preform. As shown in Fig. 10 c), the temperature in the bulk remained on the same level throughout the process, which enabled imposing large bites and assumed feed length, whereas the surface was not cooled down below the forging regime.

3.2. Numerical modeling of heat treatment

After being shaped and machined to approximate dimensions, the component underwent a crucial heat treatment phase, where its final properties were

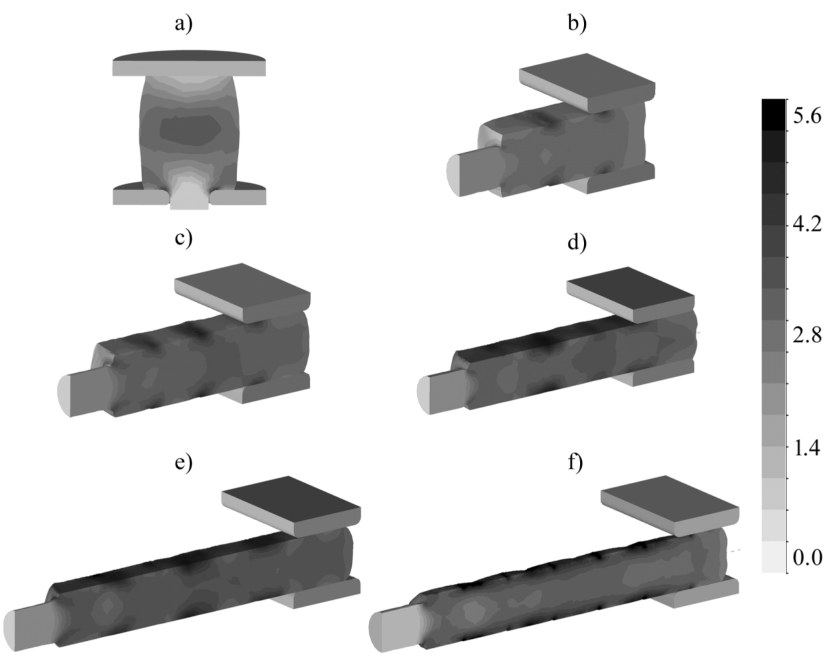

Figure 8. *Numerically estimated distribution of effective strain (ε_H) on the axial section of the forged shaft in consecutive forging passes (a-f)*

achieved. To predict the fractions of structural constituents resulting from the two assumed heat treatment schedules in this study, numerical simulations of cooling were conducted. The simulated outcomes of employing water-air and oil as quenchants are presented in Figure 11. The utilization of distinct quenching media had a discernible, and to some extent, intriguing impact on the cooling curves.

A noteworthy observation could be seen in the cooling curves' behavior. In the initial quenching stage with oil (Figure 11a), the surface cooling rate initially appeared higher than that of water spray (Figure 11c), only to gradually decelerate below 400 °C. This phenomenon stemmed from the inherent cooling characteristics of the media. The heat exchange maximum of water spray was observed at lower temperatures, where it attained a high heat flux down to the ambient temperature. A cooling interruption induced a reversal of the heat gradient, resulting in the surface temperature rising above 220 °C.

The finite element method (FEM) calculated cooling curves offer insights into the resulting microstructure. Quenching with oil, on one hand, leads to a continuous cooling process with a consistent rate, giving rise to finer bainite structures with relatively thicker lamellae and pearlite spacing. Conversely, water spray quenching, on the other hand, yields a gradual reduction in the cooling rate, ultimately reaching a pseudo-isothermal plateau within the 220-300 °C range.

While the illustrative temperature plots, along with numerically modeled transformation curves, provide a visual representation of potential transformation products, a quantitative analysis was carried out to estimate the fractions of transformation products (Figure 11 b, d). The outcomes revealed that quicker bulk cooling during water quenching generated a somewhat larger fraction of bainite with a smaller quantity of pearlite and ferrite. On the other hand, prediction of structural fractions of material quenched in oil suggested significant amount of ferrite, which came along with metallographic analysis. On the strength of validation by metallographic methods of measuring volume fraction, overestimation of ferrite content in simulation of spray-quenching was concluded. According to measurement with an array of points method, which assumed that fraction of points falling

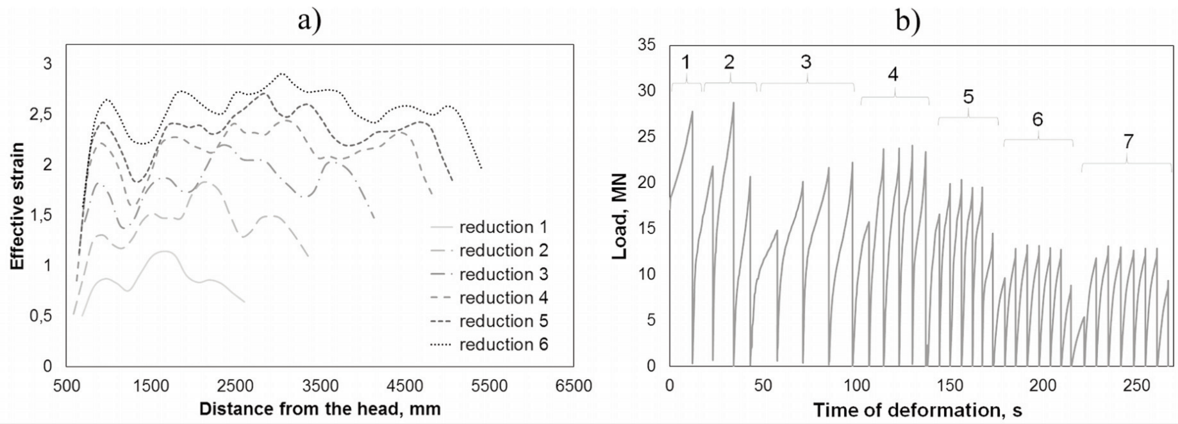

Figure 9. *Results of numerical calculations: a)* ε_H *in the core of the shaft, b) forging load in consecutive operations (1-upsetting, 2÷7 – cogging passes) of open-die forging sequence*

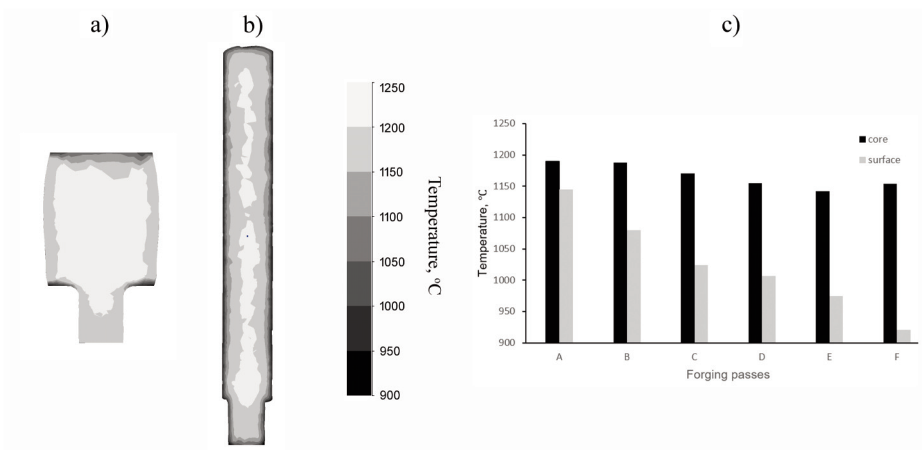

Figure 10. *Numerically calculated temperature distribution after: a) upsetting operation, b) final pass of cogging, and c) plot of average temperature on the surface and in the axis of the shaft*

into given phase fields equaled its volume fraction in the microstructure, carried out for population of 600 points at 6 independent micrographs, showed there was no ferrite in water-quenched section at all, whereas the microstructure of oil-quenched shaft showed in total of 32% ferrite and 68% pearlite + bainite, and at the depth of a half of radius: 22% ferrite, 23% bainite balanced by pearlite. Contrary to the axis, at the fractions of spray-quenched steel were similar, 19% ferrite, 28% pearlite balanced by bainite. Nevertheless, the differences were small enough to assume correctness of the both cooling schemes, hence none of the cycles was excluded from the experimental tests.

Alongside with transformation products resulting from quenching and tempering, amount and form of precipitates available for grain structure control was equally important in the aspect of microstructure control. For rough interpretation of possible amount of precipitates and their kind, equilibrium analysis of volume fraction was carried out. The results of the modeling shown in diagram in Fig. 12 indicate potential types of carbonates to play role in microstructure control on cooling of recrystallized austenite before and while transforming to bainite (plus ferrite present in the axis of the shaft) and pearlite.

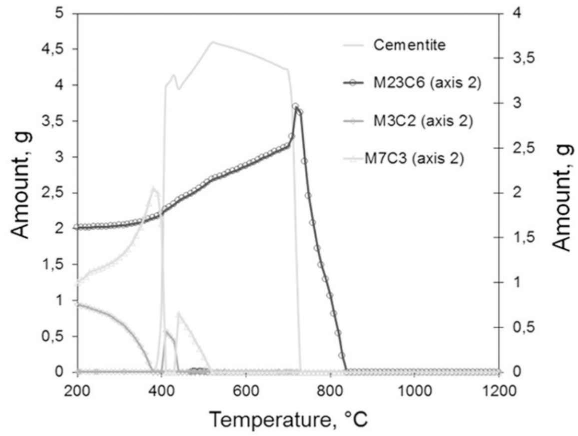

Figure 12. *Precipitates predictions in for equilibrium conditions*

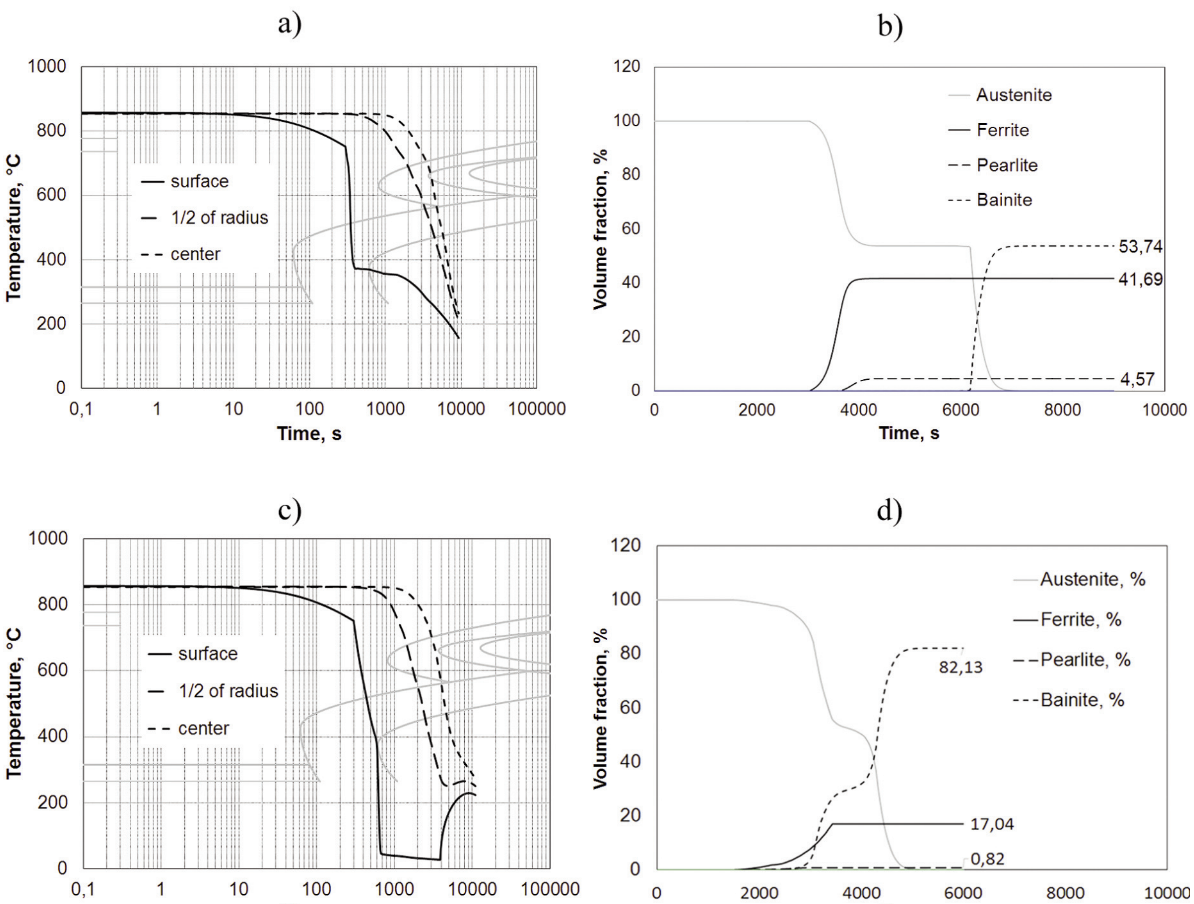

Figure 11. *Plots of FEM calculated cooling curves on the depth of the shaft on the background of theoretical CTT diagrams of modified AISI 4140 grade: a) cooling curves for quenching with a) oil, b) calculated volume fractions in the axis of the shaft after oil quenching, c) cooling curves for quenching in water spray and air, d) calculated volume fractions in the axis of the shaft after water spray quenching*

3.3. Microstructure analysis

The metallographic findings are presented in Figure 10. With the exception of the bainite-martensite zone near the undersurface, approximately one-fourth of the radius, all air-cooled microstructures, whether in their as-forged or normalized states, consisted of pearlite and former-austenite grain-boundary ferrite.

The as-forged austenite grain size varied from 100 to 200 µm in the surface regions to over 500 µm, occasionally even reaching 2 mm, within the axial zone. This scale of variation proved sufficient to address crucial quality considerations in two key respects. Firstly, it ensured the fulfillment of ductility requirements in the regions subjected to quality tests. The structural components, as indicated by numerical quenching simulations and corroborated by experimental evidence, alongside the grain size revealed through metallography, including both bainite (or pearlite) colony size and interlamellar spacing, form a solid foundation for intrinsic plasticity in the ingot's core. This intrinsic plasticity was of paramount importance in the production of a reliable forged part and, subsequently, in the overall performance of the final product.

Regardless of whether the intention was to drill or manipulate the shaft on a mandrel, be it a traditional or hollow ingot, the quality of forged shafts depended on the achievement of the minimum strain threshold in the core [47, 48]. In cases where the axial zone was removed, such as in drilling applications, controlling the grain became impossible. Conversely, in cases involving mandrel forging, which encompassed punching actions demanding superior forgeability due to the complex stress state and high strains involved, grain control remained a critical factor.

Surprisingly, the distribution of grain sizes did not follow a pattern where larger grains were found farther from the surface. In the middle area, there were grains that were as big as, or even bigger than, those in the core. This pattern persisted even after the material underwent its final heat treatment. The reason behind this phenomenon was rooted in the existence of a layer on the surface that was resistant to deformation, alongside a central zone that experienced the least deformation. In between these two zones, there was a moderate level of strain that occurred naturally. Whether the core was undergoing enough deformation to trigger recrystallization or not, the intermediate zone experienced only slight deformation, which fell short of the critical strain needed for dynamic recrystallization to start [49]. Nevertheless, despite this mild deformation in the intermediate zone, the presence of a small number of grain nuclei allowed for unhindered growth. This unrestricted growth led to the development of large grains at the expense of smaller ones. Consequently, this resulted in a coarse-grained

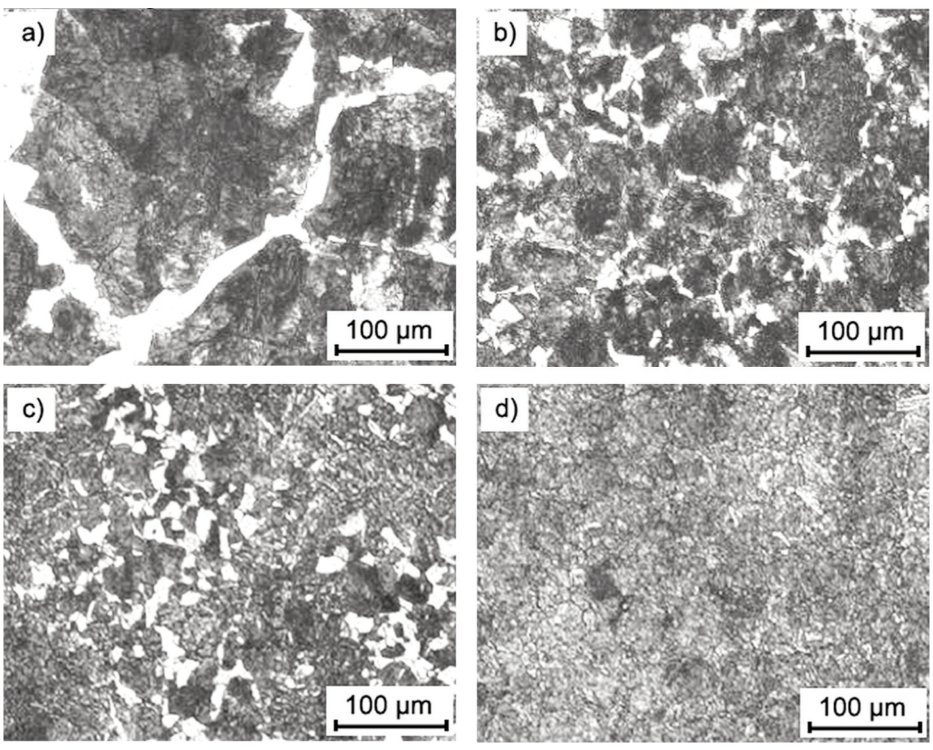

Figure 13. *Microstructure observed in the axis of the shaft forged from16 Mg ingot of steel AISI 4140 after essential stages of processing: a) forging, b) primary heat treatment, c) and d) final heat treatment – quenching with oil and water-air, respectively*

structure. In situations where grain boundaries were pinned by particles, a dual structure of grain sizes, known as a bimodal grain structure, could emerge [26]. This is the situation was found in this case. As seen in Fig. 14, summarizing evolution of microstructure in the axis of the shaft in consecutive stages of processing the abnormally grown grains to a degree were refined during subsequent normalized annealing. An intriguing observation was that this grain refinement during normalization was notably more effective in the central region of the shaft. Two explanations emerged to the forefront.

Firstly, the nonuniformity of temperature during heating results in the dissolution of chromium carbonate precipitated throughout the shaft, except for the center. Consequently, the pinning effect weakens in the intermediate zones. Previous studies [12, 24, and 28] highlighted that during the initial cogging passes, the core zone remained unaffected due to strain levels below the threshold for recrystallization. In contrast, the intermediate zones experienced a critical level of strain, triggering grain restoration. The resulting few nuclei formed in this process continued to grow without constraints, leading to excessive grain growth. However, although that strain level was sufficient for onset of recrystallization, abnormal grain growth occurred as not enough stored energy for grain refinement was provided [26]. Its effect may be related to increasing interparticle spacing or dissolution of chromium carbides, which took place at about 1100 °C [49]. Examination of as-forged microstructure indicated significant grain refinement down to less than a half of radius (315 mm).

Secondly, discontinuous character of deformation had to do with in cogging process resulted in limited range of large deformation and adjacent field of deformation gradient outwards. Thus, strain equal to critical was sure to occur in one stroke or as a conjunction of two low-strain zones from consecutive strokes. As explained by numerically estimated strain distribution, nonuniformity of deformation was reported. In the aftermath of the cogging operations, surface zone received twice as much total equivalent strain as the core, which was natural for cogging sequences in open-die forging of heavy components and was accounted for while determining the total

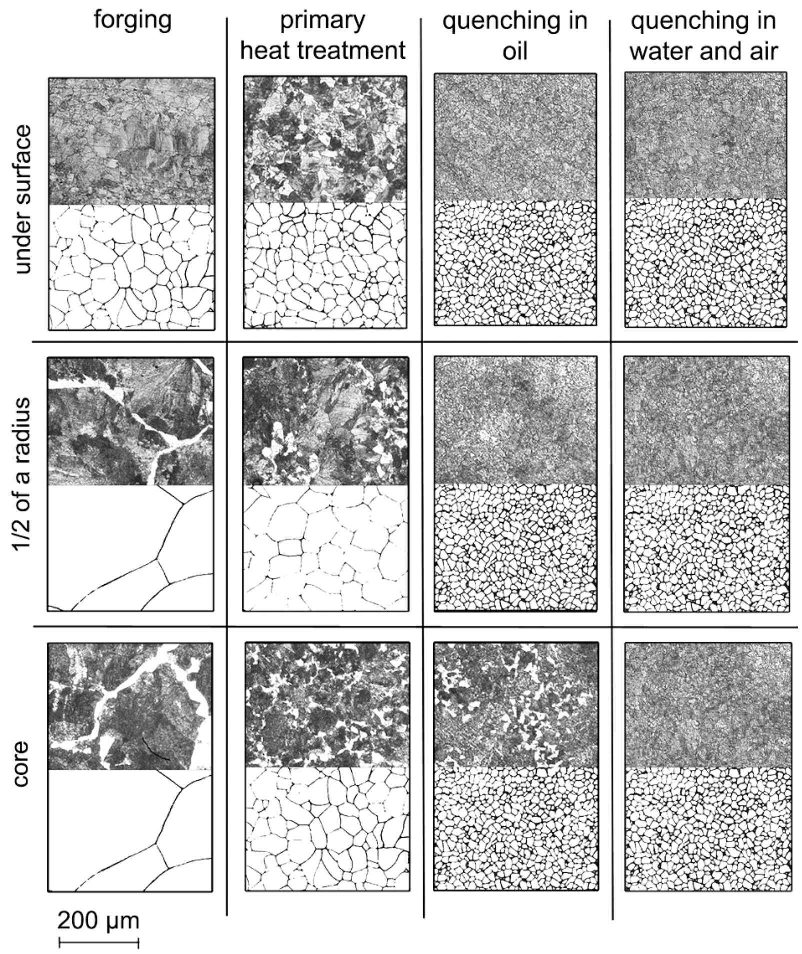

Figure 14. *Microstructure after essential stages of processing 16 Mg ingot of steel AISI 4140 in selected locations on cross-section with its interpretation in accordance with ASTM E112-10*

amount of work to be obtained within forging sequence. Moreover, the core zone seemed to contain finer grained microstructure than the intermediate one (1/2 of radius). This conclusion can be justified by above mentioned nonuniformity of strain on cross-section and the nature of static recrystallization kinetics, which was believed to do with prevailing mechanism of microstructure reconstruction in open-die forging on relatively slow action hydraulic presses.

Both of these concurrent cases can take place in the analyses process.

Microstructure analysis of the core zone of the shaft served as an illustration of how forging conditions influenced the effectiveness of grain structure restoration. However, given that open-die forged heavy shafts were frequently drilled, the microstructure's condition in the intermediate zone, which eventually became the inner surface, was equally significant. This area often experienced strain-induced abnormal grain growth, prompting the question of whether it was adequately refined. Therefore, in addition to the core of the shaft, microstructure examination was conducted in the surface zone and intermediate zones near the half-radius depth.

To prepare such microstructure before heat treatment, a normalizing annealing process was employed. As evident from the micrographs in Figure 14, normalized grains exhibited greater uniformity in the bulk. Although variations between the undersurface and core zones persisted, they were relatively minor in comparison to the achieved grain refinement, which was further enhanced by the final heat treatment. This final heat treatment, involving oil/water quenching followed by high tempering, yielded a tempered bainite microstructure with a grain size of 9 ASTM in the bulk.

Variation of cooling rate allowed concluding little effect of cooling rate of the investigated cooling methods on grain size. However, as seen in Fig. 14, quenching with oil led to the precipitation of grain boundary ferrite in the core, which could reduce strength levels. Conversely, the presence of ferrite could contribute to improved resistance to cracking and enhanced ductility [20, 43]. Employing water for quenching the shaft could enhance strength properties, although the risk of thermal cracking became prominent in larger sections. To mitigate the challenges associated with thermal stress, sequential quenching, polymer quenching, or spray quenching [4, 29] can be considered. These cooling methods yield sufficient cooling rates to eliminate diffusion-driven transformation products in the core, thereby reducing stress gradients in the bulk.

Both of the applied heat treatment schedules yielded the necessary fractions of structural constituents. However, the differing temperature profiles over time influenced the extent of quenching-induced thermal stresses and the potential for auto-tempering or partitioning.

Incorporating an isothermal hold in the martensite field during the second step of interrupted cooling, specifically air cooling, enabled temperature equalization. This precision in temperature control during cooling aids in regulating the composition of structural constituents, including untransformed austenite. This particular adjustment was believed to enhance the resistance to cracking in heat-treated components [43].

The microstructural evolution observed during key processing stages of the analyzed heavy forged shaft is succinctly depicted in Figure 15. The most significant variation in grain size was evident in the as-forged state. Stringent forging conditions resulted in substantial grain size refinement primarily in the surface regions. Despite employing large bites, the occurrence of inevitable abnormal grain growth after reheating led to grain growth of 1–2 ASTM, with grain sizes reaching around 0.5 mm. These grown grain dimensions were smaller than those typically observed in less controlled economy cogging processes, where sizes could extend into the range of a few millimeters. Microstructure of the forged shaft, substantially

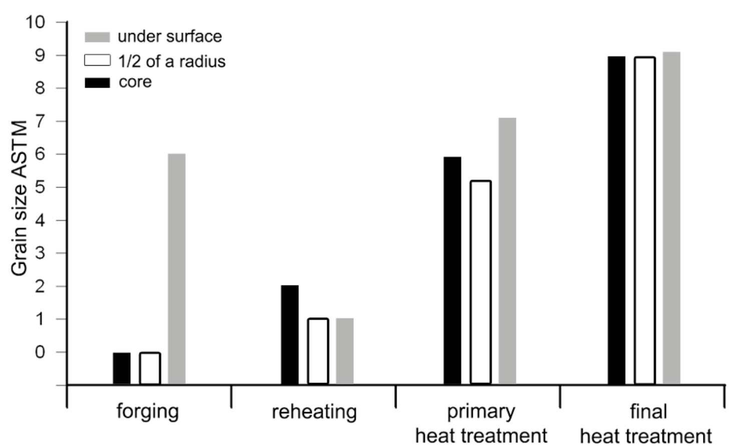

Figure 15. *Grain size in consecutive stages of processing 16 Mg ingot*

improved during preliminary heat treatment, was finally refined to 9 ASTM, which allowed producing after tempering, correspondingly, 44÷48 and 85÷122 J/cm^2 V-notch impact strength in the most crucial area of the forged shaft. Hence, in addition to quantitative results, it can be concluded that if response to normalizing brings about comprehensive grain refinement, exacerbated forging conditions may be smoothed out and energetically inadequate in the light of effect of subsequent heat treatment on grain size. Increasing number of potential microscopic obstacles, grain refinement is bound to improve cracking resistance and strength properties of the high-duty parts [21, 50]. Additions of vanadium can amend for detrimental effects of inevitable transition zones of strain degree, which can minimize the major cause of abnormal grain growth.

4. Conclusions

The study focused on analyzing the response of as-forged material to various processing routes. Employing significantly larger bites and drafts in a multistage sequence of upsetting and cogging was found to be beneficial in achieving uniform strain distribution and homogenous microstructure in heavy forgings, both after forging and subsequent heat treatment.

Effective strain of 2.5 or higher was observed throughout the entire length of the shaft, which was concluded to breakdown of ingot primary structure, as well as closing the internal porosity down to the axial zone.

The most significant nonuniformity of grain size was observed in as-forged condition. Here, unavoidable abnormal grain growth occurred due to static recrystallization, resulting in grain sizes of 1–2 ASTM. Through preliminary heat treatment, the microstructure of the forged shaft was refined to a grain size of 9 ASTM, which allowed producing after tempering, correspondingly, 44÷48 and 85÷122 J/cm^2 V-notch impact strength. It showed, that while its hardenability enabled bainitic structure in the bulk, analyzed grade 4140 was prone to undergo normalization providing fine grain. The applied values of feed ratio were in favor of both quality and productivity rate, as long as the press capacity accommodated increased work of deformation.

Improved strain uniformity attributed to large feed length formed a good base for next heat treatment, resulting in finer pearlite or bainite colonies. Application of accelerated interrupted cooling with water spray and natural air increased overcooling rate attributing to finer grain and interlammelar spacing in pearlite and/or bainite and martensite sheaves promoting good combination of strength and ductility.

Both of the applied heat treatment schedules were satisfactory in terms of fractions and morphology of structure constituents, nevertheless routes of temperature in water-air quenching provided opportunity to reduce thermal stresses and auto-tempering or partitioning.

Modification of chemical composition allowed grain refinement and homogeneity of grain size during heat treatment. Observed grain size evolution during cooling, indicated effective action of grain refining mechanisms, among which suppressing of grain growth due to pinning of grain boundaries was noticed, providing of privileged sites for nucleation and affecting hardenability may be attributed to the presence of V precipitates, indicated by phases analysis. Combination of the two modifications resulted in prevention from abnormal grain growth occurring in lean alloyed steels at critical strain.

As indicated by the results, cooling conditions were of primary importance in controlling the final microstructure and properties of forged heavy parts. Proper cooling regime could amend for nonuniformity of strain and abnormal grain growth, which were found as natural and frequently, unavoidable phenomena in open-die forging process of heavy sections.

Increased feed ratio of 0.7÷0.9 in synergy with increased V content for simplification of cost-effectiveness of the technological forging conditions process for production of uniform microstructure of high-duty heavy forgings made of Cr-Mo medium carbon heat treatable steel.

However, the variation of cooling media in a range dictated by mechanical properties requirements and acceptable stress level, had effect on volume fractions of structural constituents and final strength properties. Nevertheless, the effect of sequential cooling with media of different cooling efficiency, replacing use of plain oil allowed considerable control of microstructure on the depth of a section with reduction of thermal stresses.

Acknowledgments

Financial assistance of Polish Ministry of Science within subsidiary funds under agreement 16.16.110.663 is acknowledged. Authors address thanks to S. Dębakowski, G. Kozieł and J. Kowalski for supervising the forging tests.

Authors' contributions

P. Skubisz: conceptualization, literature review, methodology, data preparation, modeling of heat treatment, writing original draft, review of the final version; Ł. Lisiecki: numerical modeling of forging, literature review, experimental tests, graphics, manuscript preparation, review of the final version

Data Availability Statement

The data are available and can be shared upon reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Y. Tanaka, I. Sato, Development of high purity large forgings for nuclear power plants, Journal of Nuclear Materials, 417, (1–3)(2011) 854–859. https://doi.org/10.1016/j.jnucmat.2010.12.305

[2] S.H. Kim, W.S. Ryu, I.H. Kuk, Microstructure and mechanical properties of Cr-Mo steels for nuclear industry applications, Journal of the Korean Nuclear Society, 31 (6) (1999) 561–571. https://scienceon.kisti.re.kr/srch/selectPORSrchArticle.do

[3] K. Suzuki, I. Sato, M. Kusuhashi, H. Tsukada, Current steel forgings and their properties for steam generator of nuclear power plant, Nuclear Engineering and Design, 198 (1) (2000) 15–23 . https://doi.org/10.1016/S0029-5493(99)00273-3

[4] A. Pola, M. Gelfi, G.M. La Vecchia, Simulation and validation of spray quenching applied to heavy forgings, Journal of Materials Processing Technology, 213 (12) (2013) 2247–2253. https://doi.org/10.1016/j.jmatprotec.2013.06.019

[5] G. Quan, Y. Tong, G. Luo, J. Zhou, A characterization for the flow behavior of 42CrMo steel, Computational Materials Science, 50(1) (2010) 167–171. https://doi.org/10.1016/j.commatsci.2010.07.021

[6] Y.C. Lin, M.S. Chen, J. Zhong, Effect of temperature and strain rate on the compressive deformation behavior of 42CrMo steel, Journal of Materials Processing Technology, 205 (1–3) (2008) 308–315. https://doi.org/10.1016/j.jmatprotec.2007.11.113

[7] E. Kohls, C. Heinzel, M. Eich, Evaluation of hardness and residual stress changes of AISI 4140 steel due to thermal load during surface grinding, Journal of Manufacturing and Materials Processing, 5 (3) (2021) 73. https://doi.org/10.3390/jmmp5030073

[8] G. Kang, Y. Liu, J. Ding, Multiaxial ratchetting-fatigue interactions of annealed and tempered 42CrMo steels: Experimental observations, International Journal of Fatigue, 30 (12)(2008) 2104–2118. https://doi.org/10.1016/j.ijfatigue.2008.06.002

[9] A. Zieliński, J. Dobrzański, H. Krztoń, Structural changes in low alloy cast steel Cr-Mo-V after long time creep service, 25 (1) (2007) 33–36. http://www.journalamme.org/papers_vol23_2/1047.pdf

[10] L. Keränen, M. Kangaspuoskari, J. Niskanen, Ultrahigh-strength steels at elevated temperatures, Journal of Constructional Steel Research, 183(2021) 106739. https://doi.org/10.1016/j.jcsr.2021.106739

[11] I.A. Borisov, Properties and defects of large forgings, Metal Science and Heat Treatment, 40 (8) (1998) 316–318. https://doi.org/10.1007/bf02466218

[12] J. Sinczak, J. Majta, M. Glowacki, M. Pietrzyk, Prediction of mechanical properties of heavy forgings, Journal of Materials Processing Technology, 80–81 (1998) 166–173. https://doi.org/10.1016/S0924-0136(98)00104-6

[13] B.A. Marinkovic, R.R. De Avillez, S. Kessler Barros, F.C. Rizzo Assunção, Thermodynamic evaluation of carbide precipitates in 2.25Cr-1.0Mo steel for determination of service degradation, Materials Research, 5 (4) (2002) 491–495. https://doi.org/10.1590/S1516-14392002000400016

[14] H. Hoseiny, U. Klement, P. Sotskovszki, J. Andersson, Comparison of the microstructures in continuous-cooled and quench-tempered pre-hardened mould steels, Materials and Design, 32 (2011) 21–28. http://dx.doi.org/10.1016/j.matdes.2010.06.045

[15] Q. Ma, Z. Wang, Y. Zhong, The mechanism of faults originating from inclusions in the plastic deformation processes of heavy forging, Journal of Materials Processing Technology, 123(2022) 61–66. https://doi.org/10.1016/S0924-0136(02)00053-5

[16] K. Chadha, D. Shahriari, M. Jahazi, Modeling metadynamic recrystallization of a die steel during ingot breakdown process, MATEC Web Conf., 80 (2016) 1–5. https://doi.org/10.1051/matecconf/20168006004

[17] S.Y. Lee, S.I. Lee, B. Hwang, Sensitivity of microstructural factors influencing the impact toughness of hypoeutectoid steels with ferrite-pearlite structure using multiple regression analysis, Journal of Korean Institute of Metals and Materials, 54 (9) (2016) 637–644. https://doi.org/10.3365/KJMM.2016.54.9.637

[18] N. Kim, D.C. Ko, C.J. VanTyne, S.W. Han, D. Abolhasani, Y.H. Moon, Innovative square cogging to enhance void closure efficiency during forging of continuously cast round blooms, International Journal of Material Forming, 15 (5)(2022) https://doi.org/10.1007/s12289-022-01709-0

[19] J. Wang, P. Fu, H. Liu, D. Li, Y. Li, Shrinkage porosity criteria and optimized design of a 100-ton 30Cr2Ni4MoV forging ingot,Materials and Design, 35 (2012)446–456. https://doi.org/10.1016/j.matdes.2011.09.056

[20] J.R. Cho, W B. Bae, Y.H. Kim, S.S. Choi, D.K. Kim, Analysis of the cogging process for heavy ingots by finite element method and physical modelling method, Journal of Materials Processing Technology, 80–81 (1998) 161–165. https://doi.org/10.1016/S0924-0136(98)00183-6

[21] W.C. Pei, J.W. Dong, H.C. Ji, H.Y. Long, S.F. Yang, Study on crack propagation of 42CrMo, Metalurgija, 58 (3–4) (2019) 219–222.

[22] E. Collins, Metals Handbook, Nondestructive evaluation and quality control, vol. 17, 9th Edition, ASM International, Metals Park, OH (1992) p.3470.

[23] T.G. Byrer, S.L. Semiatin, D.C. Vollmer, Forging Handbook, Forging Industry Association, American Society of Metals, Cleveland, Ohio, 1985.

[24] H. Kakimoto,, T. Arikawa, Prediction of surface crack in hot forging by numerical simulation, Procedia Engineering, 81(2014)474–479. https://doi.org/10.1016/j.proeng.2014.10.025

[25] M. Wolfgarten, D. Rosenstock, F. Rudolph, G. Hirt, New approach for the optimization of pass-schedules in open-die forging,International Journal of Material Forming, 12 (6) (2019) 973–983. https://doi.org/10.1007/s12289-019-01471-w

[26] J. Krawczyk, H. Adrian, The kinetics of austenite grain growth in steel for wind power plant shafts, Archives of Metallurgy and Materials, 55, (2011) 91–99.

[27] T.H. Zhou, H.S. Zurob, Abnormal and post-abnormal

austenite grain growth kinetics in Nb-Ti microalloyed steels, Canadian Metallurgical Quarterly, 50 (4) (2011) 389–395.
https://doi.org/10.1179/1879139511Y.0000000002

[28] G. Banaszek, A. Stefanik, S. Berski, Computer and laboratory modelling of the analysis of closing up of metallurgical defects ingots during free hot forging, Metalurgija, 44 (1) (2005) 25–29.
https://hrcak.srce.hr/file/188930

[29] M. Kukuryk, The analysis of deformation and forecasting microstructure in the forging process of the X6CrNiTi18-10 austenitic steel, Archives of Metallurgy and Materials, 63 (1) (2018) 393–401.
https://doi.org/10.24425/118953

[30] A. Pohjonen, P. Kaikkonen, O. Seppälä, J. Ilmola, V. Javaheri, T. Manninen, M. Somani, Numerical and experimental study on thermo-mechanical processing of medium-carbon steels at low temperatures for achieving ultrafine-structured bainite, Materialia, 18 (2021)101150.
https://doi.org/10.1016/j.mtla.2021.101150

[31] N. Kim, D.C. Ko, N. Kang, I.Y. Oh, C.J. VanTyne, Y.H. Moon, Feasibility of using continuously cast round bloom as a substitute to cast ingot in the manufacture of heavy forgings, Steel Research International, 91 (9) (2020), https://doi.org/10.1002/srin.202000079

[32] G. Khalaj, M.J. Khalaj, Modeling the correlation between yield strength, chemical composition and ultimate tensile strength of X70 pipeline steels by means of gene expression programming, International Journal of Materials Research, 104 (7) (2013)697–702.
https://doi.org/10.3139/146.110910

[33] Y.N. Guo, Y.T. Li, W.Y. Tian, H.P. Qi, H.H. Yan, Combined cellular automaton model for dynamic recrystallization evolution of 42CrMo cast steel, Chinese Journal of Mechanical Engineering, 31 (85) (2018). https://doi.org/10.1186/s10033-018-0284-8

[34] L. Zheng, D. Zheng, L. Zhao, L. Wang, K. Zhang, Novel water-air circulation quenching process for AISI 4140 steel, Metals and Materials International, 19 (6) (2013)1373–1376. https://doi.org/10.1007/s12540-013-6034-7

[35] Q. Yu,Y. Sun, Abnormal growth of austenite grain of low-carbon steel, Materials Science and Engineering: A, 420(1–2), (2006) 34–38.
https://doi.org/10.1016/j.msea.2006.01.027

[36] X. li Wen, Z. Mei, B. Jiang, L.C. Zhang, Y. Z. Liu, Effect of normalizing temperature on microstructure and mechanical properties of a Nb-V microalloyed large forging steel, Materials Science and Engineering: A, 671 (2016) 233–243.
https://doi.org/10.1016/j.msea.2016.06.059

[37] H. Gwon, J. K. Kim, S. Shin, L. Cho,B.C. De Cooman, The effect of vanadium micro-alloying on the microstructure and the tensile behavior of TWIP steel, Materials Science and Engineering: A, 696 (2016) 416–428.
https://doi.org/10.1016/j.msea.2017.04.083

[38] A. Brownrigg,G.K. Prior, Hardenability reduction in VN microalloyed eutectoid steels, Scripta Materialia, 46 (5) (2002) 357–361.
https://doi.org/10.1016/S1359-6462(01)01251-9

[39] J. J. Jonas, V.V. Basabe, C. Ghosh, Transformation of deformed austenite at temperatures above the Ae3, Materials Science Forum, 706–709 (2012) 49–54.
https://doi.org/10.4028/www.scientific.net/MSF.706-709.49

[40] M. Opiela, W. Zalecki, A. Grajcar, Influence of plastic deformation on CCT-diagrams of new-developed microalloyed steel, The Journal of Achievements in Materials and Manufacturing Engineering, 51 (2) (2012) 78–89.

[41] A. Fadel, D. Glišić, N. Radović, D. Drobnjak, Intragranular ferrite morphologies in medium carbon vanadium-microalloyed steel, Journal of Mining and Metallurgy, Section B: Metallurgy.49 (3) (2013)237–244. https://doi.org/10.2298/JMMB120820001F

[42] M. Szala, G. Winiarski, Ł. Wójcik, T. Bulzak, Effect of annealing time and temperature parameters on the microstructure, hardness, and strain-hardening coefficients of 42CrMo4 steel,Materials,13 (9)(2020).
https://doi.org/10.3390/MA13092022

[43] P. Skubisz, P. Micek, J. Sińczak, M. Tumidajewicz, Automated determination and on-line correction of emissivity coefficient in controlled cooling of drop forgings, Solid State Phenomena, (2011).
https://doi.org/10.4028/www.scientific.net/ssp.177.76

[44] J. Pacyna, A. Kokosza, R. Dziurka, Irreversible temper embrittlement, Archives of Materials Science and Engineering, 62 (2) 67–72.
http://www.amse.acmsse.h2.pl/vol62_2/6223.pdf

[45] P. Skubisz,H. Adrian, Estimation of heat transfer coefficient of forced-air cooling and its experimental validation in controlled processing of forgings, Numerical Heat Transfer. Part A Applications, 73 (8) (2018) 163-176.
https://doi.org/10.1080/10407782.2017.1421362

[46] M. Apostoł, P. Skubisz, H. Adrian, Determination of heat transfer coefficient for air-atomized water spray cooling and its application in modeling of thermomechanical controlled processing of die forgings, Materials, 15(7) (2022) 2366.
https://doi.org/10.3390/ma15072366

[47] V.A. Shamrei, S.I. Zhul'ev, New shape of forging ingot for making hollow forged products, Metallurgist, 51 (11–12) (2007) 617–623.
https://doi.org/10.1007/s11015-007-0112-3

[48] P. Skubisz, Ł. Lisiecki, J. Sińczak, Studies of the quality and cost-effectiveness of a novel concept of open-die forged powerplant main shaft, Metalurgija, 54 (2) (2015) 339-342 url: https://hrcak.srce.hr/128956

[49] P. Kawulok, P. Opěla, Petr, I. Schindler, R. Kawulok, S. Rusz, M. Sauer, K. Konečná, Hot deformation behavior of non-alloyed carbon steels, Materials, 15 (2) (2022) 595. https://doi.org/10.3390/ma15020595

[50] L. Rausa, J. Ďurica, M. Martinkovič, R. Čička, M. Pašák, P. Jurči, The influence of austenitizing temperature level on microstructure development in chromium ledeburitic tool steel, METAL 2021 - 30th Anniversary International Conference on Metallurgy and Materials, Conference Proceedings, May 26 – 28, Brno, Czech Republic (2021) 537–542, 2021.
https://doi.org/10.37904/metal.2021.4155

UTICAJ SEKVENCE KOVANJA I TERMIČKE OBRADE NA MIKROSTRUKTURU VRATILA ZA VISOKONAPONSKE TERMOELEKTRANE IZRAĐENOG OD Cr-Mo ČELIKA ULTRA-VELIKE ČVRSTOĆE

P. Skubisz*, Ł. Lisiecki

AGH Univerzitet za nauku i tehnologiju, Fakultet za metalurgiju i industrijsku informatiku, Krakov, Poljska

Apstrakt

Ovaj rad predstavlja rezultate modeliranja i ispitivanja teškog dela napravljenog od Cr-Mo legure, koji je modifikovani ultra-čvrsti čelik tipa AISI 4140 sa V-modifikacijom, obrađen kroz novi postupak kovanja u otvorenim kalupima, kao i dva alternativna načina dvostepenih ciklusa termičke obrade dizajnirana da ispune zahteve za komponente visoke snage u sektoru energetike. Korišćenjem nekonvencionalnih uslova kovanja zasnovanih na pretpostavci velike brzine i odnosa smanjenja i modifikovanja hemijskog sastava, postignuta je bolja kontrola austenitnih zrna kako bi se minimizirao problem nesrazmernog rasta zrna i/ili problema uniformnosti naprezanja. Korišćenjem modeliranja metodom konačnih elemenata, optimizovana je višestepena sekvenca skraćivanja i raspodela naprezanja pri kovanju kako bi se minimizirala varijacija naprezanja duž dužine u opsegu od 2,2 do 2,7, i korelirala sa mikrostrukturom generisanom na svakom glavnom koraku na velikim poprečnim presecima vratila. Ciklusi obrade dizajnirani metodom konačnih elemenata potpuno su potvrđeni fizičkim modeliranjem korišćenjem kovačkog bloka od 16 tona, uključujući dve alternativne strategije kaljenja: uljem i vodenim prskanjem, i vazduhom. Materijal je proučavan u stanju nakon kovanja, normalizacije i termičke obrade kako bi se posmatralo ponašanje materijala oblikovanog na visokoj temperaturi i uticaji uslova hlađenja na mikrostrukturu tokom konačne termičke obrade. Utvrđeno je da korišćenje velikih odnosa smanjenja pri kovanju i različitih uslova hlađenja omogućava suzbijanje nepoželjnih efekata neizbežnog nesrazmernog rasta zrna, rezultirajući u vrednostima od 1–2 ASTM u stanju nakon kovanja, i dostizanje 6 ASTM i 8/9 ASTM nakon kaljenja uljem i vodenim prskanjem, što je omogućilo odgovarajuću udarnu čvrstoću s zareznim probijanjem od 44 do 48 i 85 do 122 J/cm^2 u kritičnom regionu kovanog vratila nakon temperiranja.

Ključne reči: *Vruće kovanje; Kovano vratilo za termoelektranu; Cr-Mo čelik visoke čvrstoće AISI 4140; Skraćivanje; Kovanje u otvorenim kalupima; Nesrazmerni rast zrna*