SELECTED ASPECTS OF MULTI-STAGE HOT FORGING OF 80MnSi8-6 STEEL

[1]Marek WOJTASZEK, [2]Grzegorz KORPAŁA, [3]Magdalena Barbara JABŁOŃSKA, [1]Łukasz LISIECKI, [1]Krystian ZYGUŁA, [1]Kamil CICHOCKI, [1]Wiktoria SKONIECZNA, [2]Michał PUŁAWSKI, [2]Urlich PRAHL

[1]AGH University of Krakow, Faculty of Metals Engineering and Industrial Computer Science, Krakow, Poland, EU, wojtaszek@agh.edu.pl, lisiecki@agh.edu.pl, kzygula@agh.edu.pl, cichocki@agh.edu.pl , skoniecz@agh.edu.pl

[2]University TU Bergakademie Freiberg, Institut für Metallformung, Freiberg, Germany, Grzegorz.Korpala@imf.tu-freiberg.de, michal.pulawski@imf.tu-freiberg.de, Ulrich.Prahl@imf.tu-freiberg.de

[3]Silesian University of Technology, Faculty of Materials Engineering, Katowice, Poland, EU, magdalena.jablonska@polsl.pl

https://doi.org/10.37904/metal.2024.4873

Abstract

Designing processes for producing responsible structural elements from steel in the hot forging process requires knowledge of the relationship between the process parameters, the microstructure that is formed under the assumed deformation conditions as well as the quality and properties of the forgings. The analysis of the microstructure after deformation allows the identification of phenomena occurring during hot processing, such as work hardening, recovery and recrystallization. On this basis, it is possible to determine both favorable sets of deformation parameters and to identify their combinations that lead to the risk of microstructural defects. However, during multi-stage open-die forging on hydraulic presses, the deformation rate does not change significantly, but the temperature gradually decreases during subsequent operations. Then, if necessary, the temperature is raised to the upper limit during intermediate reheating. As a result, the process is often carried out over a wide temperature range and cannot be maintained within a favorable temperature range. Selected results of comprehensive tests were presented, which were aimed at controlling the state of the microstructure and, therefore, the properties of forgings made of 80MnSi8-6 steel shaped in multi-stages. This goal was achieved by analyzing and controlling subsequent stages of the forging process, paying particular attention to the quality of the shape. To perform this research task, numerical modeling using the finite element method and forging tests in laboratory conditions were used.

Keywords: Multi stage forging, nanobainitic steels, FEM modeling, microstructure

1. INTRODUCTION

Steel is continuously one of the fundamental and most widely used engineering material. This is because they are produced using technologically mastered processes and are characterized by high properties [1]. Bainitic steels are becoming increasingly important in technology [2]. This group includes 80MnSi8-6 steel. Bainite is composed of plates of carbon-saturated ferrite doped with other phases, such as residual austenite or carbides [3]. A typical bainite contains ferrite with an average length of about 100 μm and a thickness of about 0.2-0.5 μm [4]. However, the size scale of bainite can be adjusted from tens of nanometers to hundreds of micrometers [5]. In this way, the properties of the products can be influenced [6]. One possibility is to run the process in such a way that leads to a nanobainitic structure. This microstructure consists of a mixture of thin plates of bainitic ferrite separated by carbon-enriched austenite [2]. Due to their favorable combination of strength and ductility, as well as their high impact strength [6], nanobainitic steels are suitable for the production of structural components with medium to high weights. Such products are manufactured using hot open die forging operations, then the forgings are cooled in air. The next step is heat treatment carried out to obtain the desired microstructure. However, quenching large-size forgings to obtain a uniform bainitic microstructure, including nanobainite, takes several days. For this reason, the process is economically inefficient and difficult to perform with typical heating systems. Regardless of the material advantages, a condition for the implementation of the new technology is the economic aspect [7], so commercially produced nanobainitic steels must be cheap enough in production to replace expensive high-alloy steels with similar properties. This can be achieved, among other things, by designing heat treatment conditions in such a way that it can be performed at relatively low temperatures and within a technologically acceptable time [2]. An example of a material that, under carefully designed conditions, can meet the above-mentioned criteria is 80MnSi8-6 steel.

From nanobainitic steels, not only large-sized products can be open die forge, but also small batches of structural components with smaller dimensions [8]. However, small feed volumes result in rapid heat transfer to tools and surrounding. The need for a series of operations during multi-stage forging takes a long time. This is especially true for operations that proceed with a series of deformations, such as elongation. The process time depends on the dimensions of the feedstock, the magnitude of defromation and the final shape of the forging. As a result, inter-operation reheating is often necessary, which is costly, time-consuming and leads to grain growth. Therefore, the number of inter-operational reheatings should be kept to a minimum. It is also a prerequisite for obtaining nanobainite to ensure an adequate initial microstructure during hot forging. Therefore, the process must be carried out in such a way that the microstructure is homogeneous and the grain as small as possible. This requires the selection of appropriate sequences of deformations and their parameters, such as the magnitude of defroamtion and feed rate. Another key element is the correct design of the optimal number of tool sets and their shape. It is also important to take into account the fact that during hot forming there are changes in the microstructure that determine the properties of the product. These changes are related to the occurrence of dynamic recovery (DRV), dynamic (DRX), metadynamic (MRX) and static (SRX) recrystallization, as well as grain growth (GG) [10]. The occurrence of the mentioned phenomena is related to the value of deformation, temperature and time. As a result, the design of the next steps of the multistage forging process of nanobainitic steel products requires knowledge of the behavior of the material depending on the thermo-mechanical deformation conditions. Obtaining such data by experiment is time-consuming, expensive and prone to uncertainty in the quality of the results. It is more advantageous to carry out numerical modeling and then verify the results thus obtained. Nowadays, FEM is widely used, to model hot deformation processes, with measurable results including thermal analysis, development of a favorable deformation scheme, the ability to predict difficulties during production, and to develop cost reduction methods. Most often, the result of using FEM is a comprehensive analysis of the process [11], an assessment of the possibility of obtaining a defect-free product and the development of the most favorable forging process strategy. However, it is crucial that the modeling results are verified, which can be done by testing in laboratory conditions or on process lines at forging plants.

2. EXAMINED MATERIAL AND EXPERIMENTAL PROCEDURE

2.1 Characterization of 80MnSi8-6 steel in the initial state

The initial material for the study was 80MnSi8-6 steel, obtained by the processes of casting and subsequent hot pre-forming of an ingot. The chemical composition of the steel is summarized in **Table 1**, a microstructure in the as-delivered state is shown in **Figure 1**. The microstructure of the material in the as-delivered state consists of ferrite grains, a small number of perlite grains and bainite. Ferrite is observed as bright areas, perlite is seen as alternating plates of ferrite and cementite, bainite is observed as dark areas with a slate-like structure.

Table 1 Chemical composition of 80MnSi8-6 steel [wt. %].

Chemical element	C	Si	Mn	P	S	Cr	Mo	V	Fe
Content, % by mass	0.79	1.55	1.9	0.003	0.003	1.3	0.25	0.11	Bal.

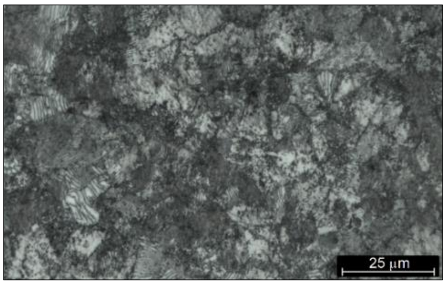

Figure 1 Microstructure of 80MnSi8-6 steel in initial state

2.2 Experimental procedure

Finite element method (FEM) modeling of a multi-stage hot open die forging of an example forging was carried out using the QForm 3D UK software. A rigid-viscoplastic model with reinforcement was used. Heat generated during deformation was taken into account. The previously developed flow curves [1] were implemented into the software. Thermal phenomena were described using thermal characteristics determined from the separate tests. The calculations were carried out in sequences, including automatic operation changes, tool changes, charge displacements between deformations and others. The temperature of the forging was analyzed, and reheating was simulated if necessary. To evaluate the microstructure in the deformed state and slow cooling, additional uniaxial compression tests were performed under isothermal conditions and at a constant strain rate, during which the deformed samples were cooled in air. Microstructure observations were made by light microscopy using a Laica DM5000M microscope. The modeling results were verified by conducting a forging test on a hydraulic press with a pressing force of 5000 kN.

3. RESEARCH RESULTS AND DISCUSSION

3.1 Results of FEM numerical modeling

The FEM analysis of a multi-step hot open die forging process was carried out, which led to fabrication of an axially symmetrical forging with an elongated shape. A schematic of the selected forging is shown in **Figure 2**.

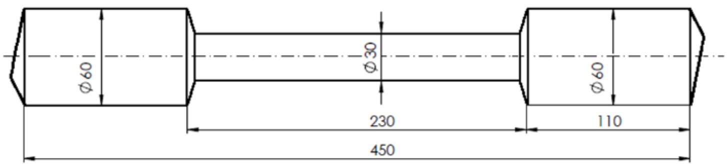

Figure 2 A schematic drawing of the forging.

The chosen shape made it possible to achieve a magnitude of deformation of 2 in the outer segments of the forging and a varying amount of deformation in its volume. Since the initial material was made in the process of hot preforming of the casting, therefore such a degree of forging was sufficient. The forging process was modeled on a hydraulic press with a pressing force of 5000 kN conducted with a constant movement speed of the upper tool of 5 mm·s^{-1}. A cylinder with a length of 140 mm and a diameter of 85 mm was taken as the feedstock. A manipulator holder with a length of 50 mm and a diameter of 40 mm was designed on one face of the feedstock. A temperature of 1250 °C was adopted as the feedstock heating and reheating temperature.

The process was optimized, modifying the parameters and conditions of subsequent operations until a acceptable result was achieved. The next step was then designed. This approach made it possible to analyze a number of variants in an acceptable time. On this basis, a favorable sequence of multi-step forging was developed, as well as tools shapes suitable for its execution. In the forging variant developed as favorable, the first stage consisted of applying charge elongation operations. These operations were carried out sequentially with forging into a square section and then into an octagonal profile. Rounding was performed in shaped tools. Then the operations for forging the inner part were modeled with spherical and shaped tools. Examples of the stages of hot multi-stage forging of a forging of the adopted shape are summarized in **Figure 3.**

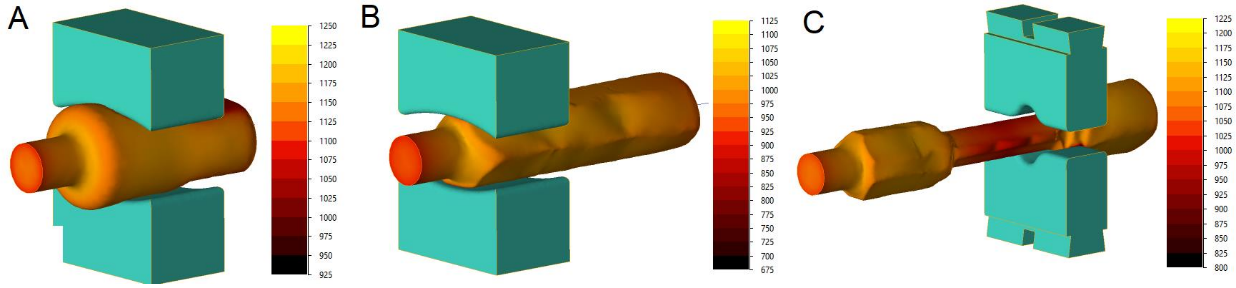

Figure 3 Selected stages of the forging process of 80MnSi8-6 steel and the corresponding temperature distributions.

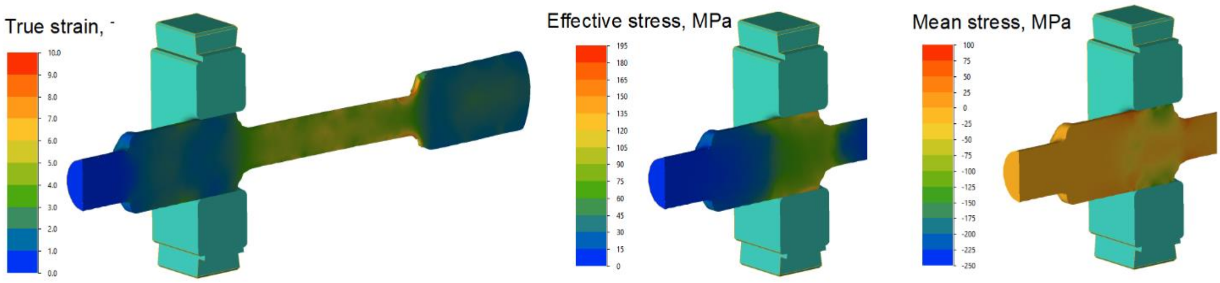

Figure 4 Selected results of FEM analysis of the forging process of 80MnSi8-6 steel - final stage.

Four sets of tools were developed to carry out the established operations. Preliminary operations were performed in flat tools. In order to remove defects found during modeling on the surface of the forging, tools with spherical faces were used. Rounding to final diameters was performed using semicircular tools, with diameters of 60 and 30 mm. **Figure 4** summarizes selected results of FEM modeling in the final deformation stage. The obtained values of true strain in the outer segments were about 2, while in the middle part they were about 6. Analysis of the temperature distributions of the forging during the successive forging stages made it possible to determine the moments of inter-operation reheating. Application of the developed configuration of operations and their parameters led to obtaining a forging with the assumed shape and free of forging defects, such as distortion or laps.

3.2 Microstructure of 80MnSi8-6 steel after deformation and cooling in air

Due to the relatively low movement speed of the hydraulic press crosshead and the associated small range of strain rates, the results of hot compression tests conducted at a strain rate of $1 \cdot s^{-1}$ are presented. Samples were first heated to a constant temperature of 1250 °C and then cooled to the test temperature and held there until a homogeneous temperature was reached in the volume. Preheating at a constant temperature led to standardization and eliminated the influence of variation in the initial microstructure on its final state. Isothermal compression process temperatures of 1000, 1100 and 1250 °C were selected. Compression was carried out until a constant true strain value of 1.2. The state of the microstructure formed under the adopted conditions is summarized in **Figure 5**. Observations were carried out on cross sections of the samples, in the plane passing through the axis of symmetry.

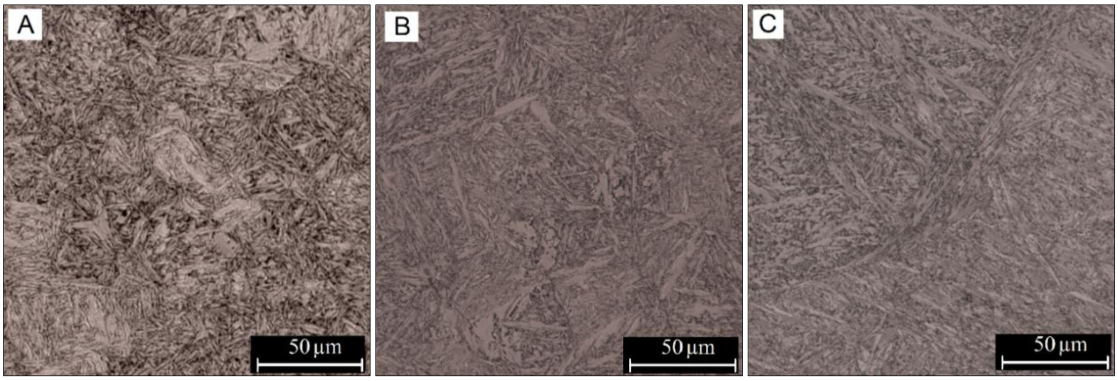

Figure 5 Effect of deformation parameters on the microstructure of air-cooled 80MnSi8-6 steel samples. Strain rate of $1 \cdot s^{-1}$, temperature: A – 1000 °C, B – 1100 °C, C – 1250 °C.

As a result of the applied procedure of heat treatment, deformation and cooling of the deformed samples, a bainitic microstructure with a slate-like structure separated by massive martensite plates was obtained. The state of the microstructure formed by deformation and slow cooling depends on the deformation temperature. The way in which the martensite plates are arranged allows qualitative evaluation of the grain boundary courses of primary austenite grains and comparison of their sizes. A systematic increase in the size of these grains is observed with an increase in the temperature of the compression test. In the case of the sample deformed at 1250 °C (**Figure 3C**), only fragments of the boundaries of these grains are visible. One reason for this may be the longer cooling time of samples deformed at higher temperatures and the associated grain growth.

3.3 Forging tests on a hydraulic press

Forging tests were conducted to verify the validity of the modeling results. The feedstock was heated in a furnace to 1250 °C and then forged on a hydraulic press, with a upper tool speed of 5 $mm \cdot s^{-1}$. The step-by-step forging procedure developed on the basis of FEM was applied. Photographs of the forging stand, the designed tools and the forging are summarized in **Figure 6**. The developed forging procedure resulted in a correctly manufactured product without defects such as distortion or laps.

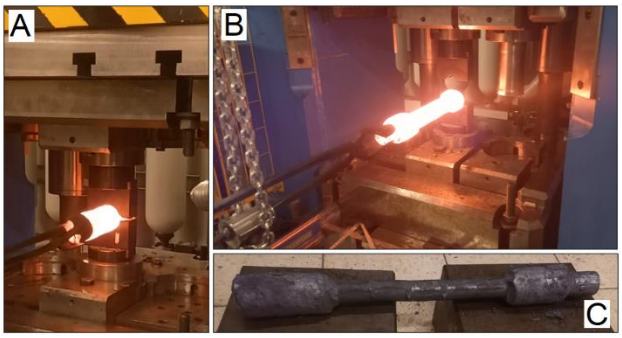

Figure 6 Results of forging tests on a hydraulic press. A,B - forging process, C - forging.

4. CONCLUSION

The conducted research and the analysis of its results have expanded the state of knowledge on the forming of products from 80MnSi8-6 steel in multi-stage forging processes. The microstructure of the steel in the initial state consisted of ferrite grains, perlite grains and bainite. Performing tests consisting of heating to 1250 °C, cooling to the test temperature, compression at a strain rate of $1 \cdot s^{-1}$ and cooling in air led to the formation of a bainitic microstructure, in which massive martensite plates were also present. The distribution of the microstructure components, especially the martensite plates, indicated that the size of the primary austenite grain increased with increasing test temperature. On the basis of FEM simulations carried out in sequences, the most favorable variant of multi-stage forging of a forging of the selected shape was selected. The favorable sequence of operations and the way they were performed were determined, tools shapes were designed and the moments of inter-operational reheating of the charge were determined. The forging procedure developed on the basis of modeling was verified in forging tests on a hydraulic press. The step-by-step application of the FEM-developed configuration of operations and their parameters led to obtaining a forging with the assumed shape and free of forging defects. According to the authors, the obtained results of modeling and testing can be useful in the design of multi-step forging technology for products made of 80MnSi8-6 steel and can serve as a starting point for further research, including the development of models of microstructure evolution during hot forging of the studied steel and their implementation into FEM analysis. Such an approach is currently being implemented by the authors of the publication.

ACKNOWLEDGEMENTS

Funding This study was funded by the National Science Centre, Poland under "M-ERA.NET 2 Call 2020", Grant No. 2020/02/Y/ST8/00107.

REFERENCES

[1] WOJTASZEK M., LISIECKI Ł., ŁUKASZEK-SOŁEK A., KORPAŁA G., ZYGUŁA K., ŚLEBODA T., JABŁOŃSKA M.B., Prahl U. Application of processing maps and numerical modelling for identification of parameters and limitations of hot forging process of 80MnSi8-6 steel. Archives of Civil and Mechanical Engineering. 2023, vol. 23, iss. 4, art. no. 240, pp. 1–22.

[2] GARCIA-MATEO C., CABALLERO F.G., SOURMAIL T., SMANIO V., GARCIA de ANDRES C. Industrialised nanocrystalline bainitic steels. Design approach. Int. J. Mater. Res. (formerly Z. Metallkd.), 2014, vol. 105, pp. 725-734.

[3] BHADESHIA H.K.D.H. Atomic Mechanism of the Bainite Transformation. J. Heat Treatm. Mat. (formerly HTM Z. Werkst. Wärmebeh. Fertigung), 2017, vol. 72(6), pp. 340-345.

[4] AVISHAN B., TALEBI P., TEKELI S. and YAZDANI S. Producing Nanobainite on Carburized Surface of a Low-Carbon Low-Alloy Steel. JMEPEG. 2023, vol. 32, pp. 211–220.

[5] ZHU, Z.; HAN, J.; LI, H.; LU, C. High temperature processed high Nb X80 steel with excellent heat-affected zone toughness. Mater. Lett. 2016, vol. 163, pp. 171–174.

[6] SOURMAIL T., GARCIA-MATEO C., CABALLERO F.G., MORELES-RIVAS L., REMENTERIA R., KUNTZ M. Tensile Ductility of Nanostructured Bainitic Steels: Influence of Retained Austenite Stability. Metals, 2017, vol. 7, pp. 31-37.

[7] CABALLERO F.G., BHADESHIA H.K.D.H., MAWELLA K.J.A., JONES D.G., BROWN P. Very strong low temperature bainite. Mater. Sci. Technol., 2002, vol. 18, pp. 279-284.

[8] LEIRO A., VUORINEN E., SUNDIN K.-G. et al. Wear of nano-structured carbide-free bainitic steels under dry rolling-sliding conditions, Wear, 2013, vol. 298-299, pp. 42-47.

[9] PRASAD, Y.V.R.K., GEGEL, H.L., DORAIVELU, S.M., MALAS, J.C., MORGAN, J.T., LARK, K.A. BARKER D.R. Modeling of dynamic material behavior in hot deformation: forging of Ti-6242. Metall. Mater. Trans. A, 1984, vol. 15, pp.1883–189.

[10] PRASAD Y.V.R.K., SASIDHARA S. (Eds.). Hot Working Guide: A Compendium of Processing Maps. ASM International, Materials Park, OH (USA), 1977, pp. 108–110.

[11] LIU, J., CUI, Z., LI, C. Analysis of Metal Workability by Integration of FEM and 3-D Processing Maps. J. Mater. Processing Technol. 2008, vol. 205, pp. 497–505.