

Article

Development of a technology of isothermal annealing with the use of the forging heat for chromium-molybdenum steel

Artur Barełkowski^{1*}, Roman Kuziak²

¹ Wrocław University of Science and Technology, Faculty of Mechanical Engineering, Department of Metal Forming, Welding and Metrology; Łukasiewicza Street 5, 50-371 Wrocław

² Łukasiewicz Research Network – Institute for Ferrous Metallurgy, Karola Miarki Street 12-14, 44-100 Gliwice

* Correspondence: artur.barelkowski@pwr.edu.pl;

Abstract: The article discusses the results of investigations performed during a thermo-mechanical treatment of forgings made of chromium-molybdenum 42CrMo4 grade steel. The treatment was realized during a regular series production. The forging process was combined with a heat treatment carried out directly after forging on a specially adapted station. Such a production technology will make it possible to eliminate the step of repeated heating of the forgings. On the example of an element of a steering gear, it was demonstrated how it is possible to perform an isothermal annealing process starting from the temperature at which the trimming of the forgings ends. During the cooling of the forgings, it is enough to maintain the temperature at the proper level in order for the exothermal phase transformation of austenite into pearlite to take place. With an appropriate design of the processing line, the heat released during the transformation could be used to maintain the applied temperature, thus limiting the consumption of energy needed to power the devices. The test results show that, with the properly selected temperature of isothermal annealing, it is possible to obtain an equilibrium ferritic-pearlitic structure in the required hardness scope. Introducing such a solution into the industrial practice would allow significant savings of the energy used for the heat treatment.

Keywords: die forging, isothermal annealing, thermo-mechanical treatment

1. Introduction

The heat treatment of forgings constitutes a large portion of the total cost of the ready element [1]. It is especially important in the case of the automotive industry, where the annual production series amount to hundreds of thousands or even millions of items [2]. Such a production scale as well as the high competition on this market generates a constant need to improve the present production processes. The costs incurred for the sake of investments can be compensated by even a slight reduction of the unit cost of the produced elements. The most popular example of a solution presently applied in forges is elimination of the typical heat treatment [3]. It can be replaced by controlled cooling of the forgings on the line BY (**B**ehandlungaufbestimmte Streckgrenze, **Y**ield-Strength – a treatment providing the material with the proper yield point) right after the forging process [4]. Such a solution should be considered already at the stage of product design [5], as it is connected with the use of appropriate grades of steel containing alloy additions causing precipitation hardening of the forgings [6] and preventing the grain from excessive growth [7].

The idea of combining metal forming with heat treatment has been implemented in practice also for unalloyed steels. However, this concerns mainly the production of steel sheets [8] as well as aluminum sheets [9], where it is possible to precisely control and steer the process through the proper selection of the strain in each pass of the material between the rollers. In the case of forgings, there is no such a possibility, as the strain results from the shape of the tools and it is constant in each operation for the given process. The method of thermo-mechanical treatment demonstrated in the study does not interfere with the production process, as it takes advantage of the heat from the forging process generated during the heating of the charge material. The energy saving results from no need of repeated heating of the forgings. In a standard case (Fig. 1a), the forgings, after the end of

the forging process, cool down to the ambient temperature. Next, they are transported to the heat treatment plant, where they are heated again above the temperature A_{c3} . After annealing, when they have obtained a structure of homogeneous austenite, the forgings are transported to another furnace with a lower temperature, in which a transformation of the structure into ferrite-pearlite takes place. In its assumption, this transformation is total, and so, after the forgings have been removed from the second furnace, they maintain the same structure, regardless of the applied cooling rate. In the case of direct isothermal annealing (Fig. 1b), the forgings, after the forging and trimming processes have finished, cool down only to the annealing temperature, after which they are placed in the furnace. The rest is carried out in the same way as in the standard case. With such a manner of treatment, it is enough to use only one furnace. A certain difficulty can be the necessity of placing the furnace in the vicinity of the forging press as well as of ensuring the proper efficiency of the thermal treatment process, which cannot be lower than the efficiency of the forging process.

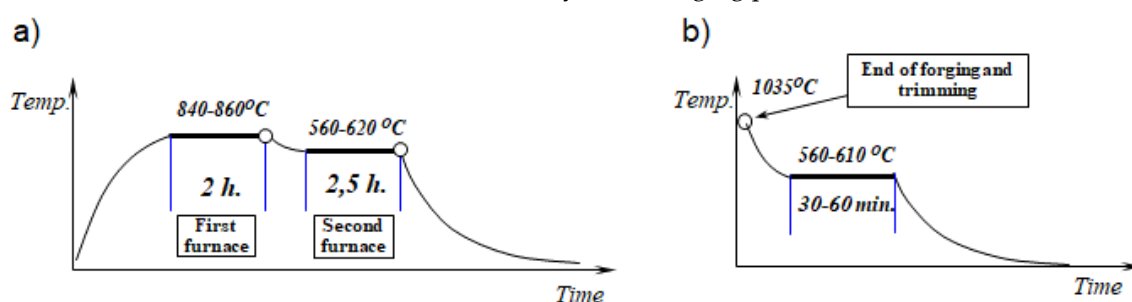


Fig. 1. Diagram of heat treatment: a) standard isothermal annealing, b) isothermal annealing directly after forging

The aim of the studies was to verify the possibility of applying a thermo-mechanical treatment under industrial conditions as well as to determine the crucial parameters of the thermal treatment process, such as the temperature and time of isothermal annealing. The second part of the research compares the obtained results with those of the thermal treatment realized in the current process of series production for this forging.

2. Test methodology

The investigations were performed during a regular series production. A Massey press with the nominal force of 13 MN and a Wilkins & Mitchell two-point crank press with the nominal force of 2 MN, used for flash trimming, were applied. The subject of analysis was a forging of an adapter used in the steering system of a motorcar. The initial material for the forging process was a round bar with the diameter of 55 mm made of 42CrMo4 grade steel. The chemical composition of this heat has been given in Table 1. According to the client requirements, the forging should characterize in a moderate hardness, within the scope of 249–280 HB. This enables an easy machining. Therefore the preferred heat treatment is isothermal annealing, which ensures a ferritic-pearlitic structure. Such a structure is easier to process than the structure of tempered martensite after a quenching and tempering process with the same hardness [10].

Table 1. Chemical composition of forgings [%]

C	Mn	Si	P	S	Cr	Ni	Cu	Mo	Al
0,42	0,78	0,29	0,011	0,010	1,07	0,12	0,24	0,16	0,022

The forgings were made in three operations (Fig. 2) and in a two-component system, due to their oblong shape with a varying cross-section. The asymmetrical orientation of the forgings in respect of each other facilitates the material distribution in the impressions. After the end of the plastic metal forming process, the flash was trimmed, and that was when the forgings were being separated. The

heat treatment was performed on a laboratorial station located directly next to the press trimming the forgings. The station consisted of an electric resistance furnace, a thermovision camera and a measuring system using a thermo-couple. In order to make the measurement possible and control the temperature during the annealing, an additional forging (pilot) was used. The forging was of the same type, except that it had been prepared and placed in the furnace beforehand, i.e. an opening had been made in it on the side of the thicker end, to the depth of 10 mm, and a thermo-couple had been mounted.



Fig. 2. View of a forging in particular operations

The temperature control began already at the moment of heating the preforms. The measurements were carried out by means of a thermovision camera, which showed the spot with the highest temperature on the thermogram. The emission factor during the measurement was set to $\varepsilon = 0,95$. The use of a thermo-couple during the forging process is not possible due to its being damaged when the material is deformed. The control of the heating and forging temperature is important in a thermo-mechanical treatment process. Overheating the material can cause excessive growth of the grains, without the possibility of improvement. In a standard heat treatment cycle, the grain refinement occurs with the secondary heating of the forgings. Fig. 3 shows a thermogram of the charge material after being heated in a heater. The temperature in the hottest spot does not exceed 1200°C.



Fig. 3. Measurement of the preform temperature at the point of removal from the heater

Fig. 4a shows a set of inserts built-in inside the press and the measured highest temperatures after the particular operations (Fig. 4b). In the first operation, after upsetting, the temperature is the lowest and equals 1035°C. This temperature is much lower than at the moment when the heating ends. In this case, it results from the long time of waiting for the preform to fall out of the heater and be placed on the die. Next, with each operation, it rises until reaching about 1100°C. The temperature increase results from the dissipation of some of the internal deformation energy in the forging despite the fact that the forging's surface is cooled down by the colder surface of the die.

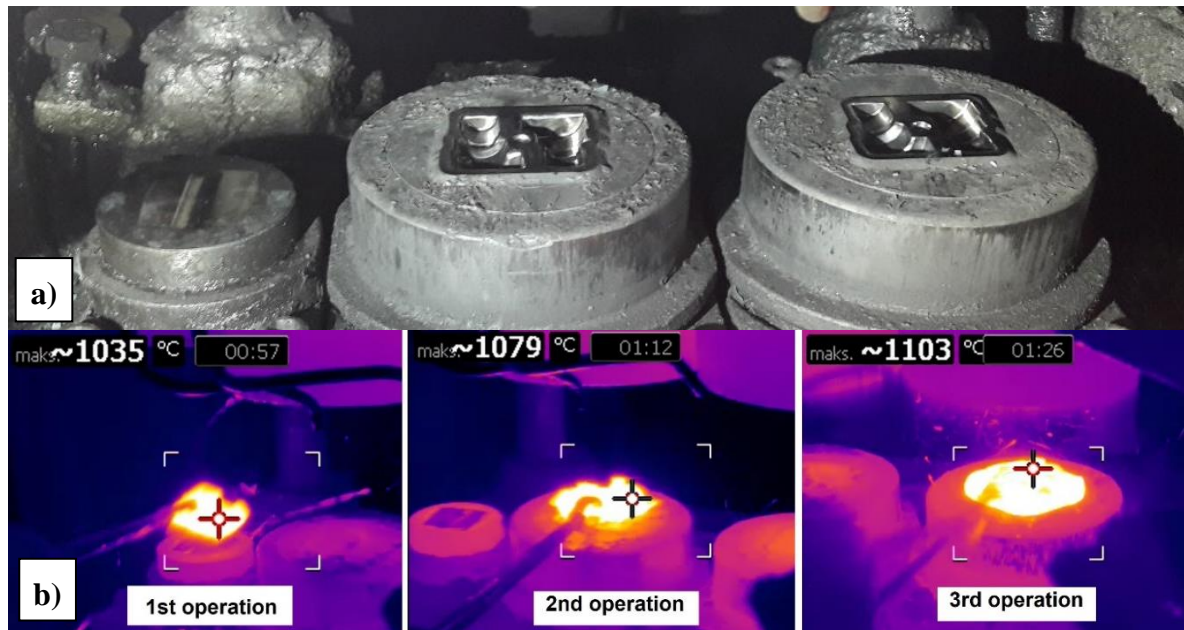


Fig. 4. Stand for forging: a) view of die inserts, b) temperature measurement after particular operations: flattening, roughing and finishing forging

After the end of the measurements of the main forging operations, a temperature measurement was made during the trimming. After the forging had been placed in the cutting board and the slide of the press performed a stroke, which separated the forgings, the temperature dropped to the value of 1035°C (Fig. 5a). After the trimming of the flash, both forgings were collected and together placed next to the press, where they cooled down freely until they reached the assumed temperature of isothermal annealing. The temperature of the forgings was controlled by means of a thermovision camera (Fig. 5b). When the assumed temperature was reached, the forgings were placed together in the furnace, where the isothermal annealing took place.

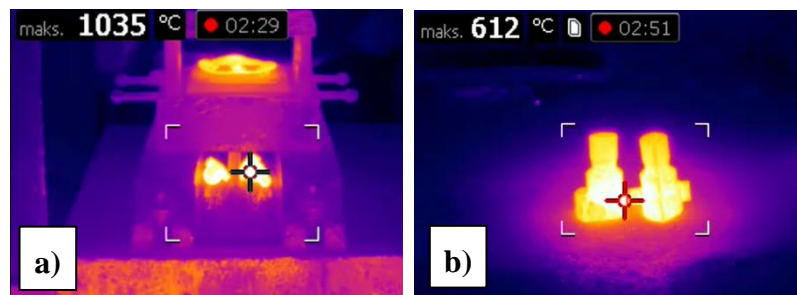


Fig. 5. Temperature measurement of forgings: a) after flash trimming, b) at the end of cooling, right before being placed in the furnace

On the basis of the TTT diagram for 42CrMo4 grade steel (Fig. 6), we can determine the approximate temperature scope in which the treatment should be performed in order to reach the assumed hardness [11]. The temperature to which the charge material heats up is much higher than the temperature of the samples used to create the TTT diagram; it can, however, be assumed that the predetermined hardness should be reached between 560°C and 610°C, with the annealing time not longer than 60 minutes.

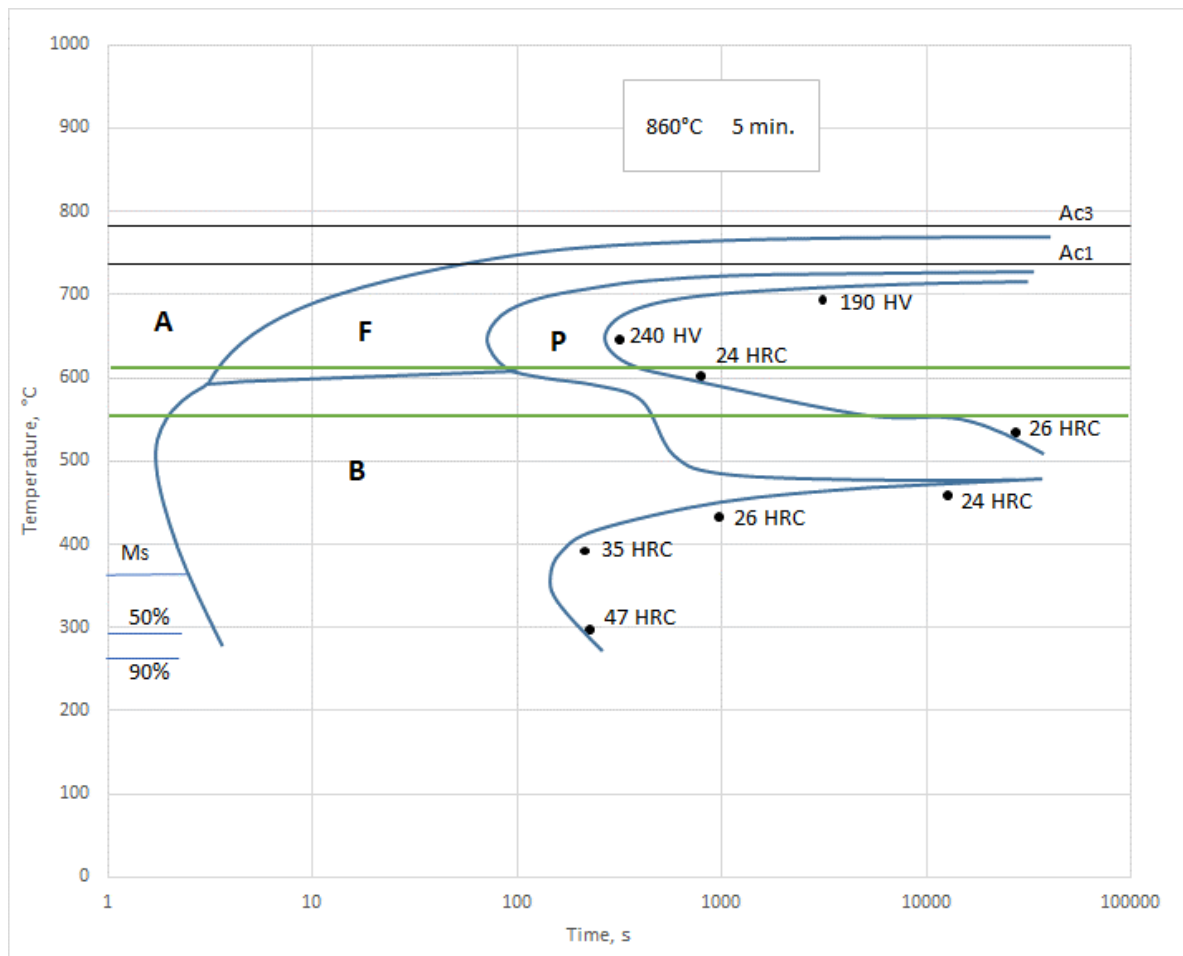


Fig. 6. TTT diagram for 42CrMo4 grade steel

In this temperature scope, we should observe transformations of austenite into ferrite and pearlite, and also partially into bainite, the amount of which increases with decrease of the temperature of isothermal annealing. Beside the temperature, the annealing time is also important; that is why the forgings placed in the furnace were removed from it after 30 and 60 minutes. The particular process parameters for all the samples have been given in Table 2.

Table 2. Temperatures and times for forgings isothermally annealed – sample denotation

		Temperature		
		560°C	580°C	610°C
Time	30 min.	A	C	E
	60 min.	B	D	F

Fig. 7 shows schematically the temperature course of the forging during the whole thermo-mechanical treatment, together with the points at which the temperature was measured. The first part of the diagram, marked with a black line, shows the temperature changes during the plastic treatment - from the moment when the heating began, through the three forging operations and the trimming of the flash until the moment when the forging was placed in the furnace. The second part of the diagram, marked with coloured lines, demonstrates the predicted course during the isothermal annealing. This course was impossible to measure during the industrial process. It can, however, be inferred from the formed microstructure, as, during the phase transformation of austenite into pearlite, heat is released. That is why the real temperature of the forgings can be different from the temperature of the pilot, and

this difference is the bigger, the larger the amount of pearlite which has been precipitated during the annealing. The use of a forging – a pilot – aimed at controlling the temperature in the furnace; however, due to a high thermal inertia of the furnace, it did not exhibit a temperature increase after the annealing of only two forgings.

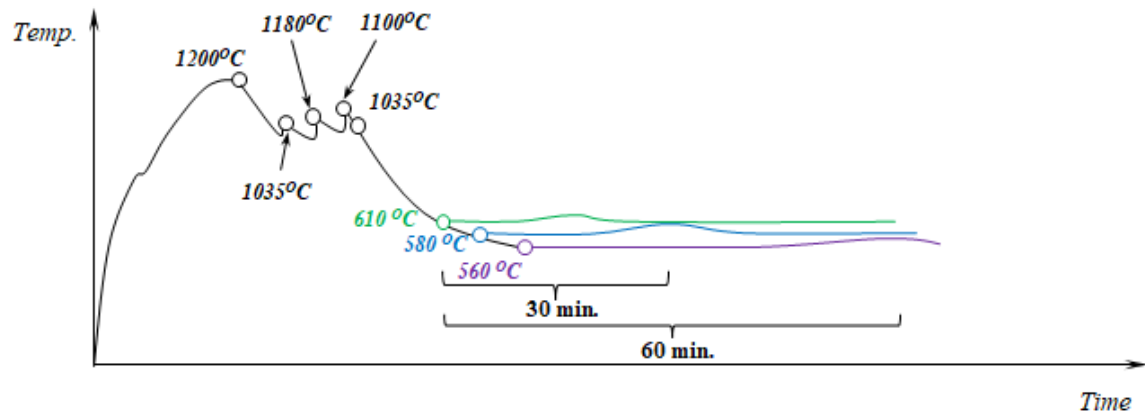


Fig. 7. Temperature course during thermo-plastic treatment

3. Material studies.

After the performed thermo-plastic treatment, macroscopic photographs were taken (Fig. 8) on the cross-sections of samples etched in Mi1Fe. The photographs show a significant diversification of structure, in the form of round zones with different colours, both between the different treatment temperatures and between the particular areas in the same forging. The most visible difference between the core of the forging and the external surface of the forging is observed in sample B annealed at 560°C for 60 minutes as well as sample C annealed at 580°C for 30 minutes.

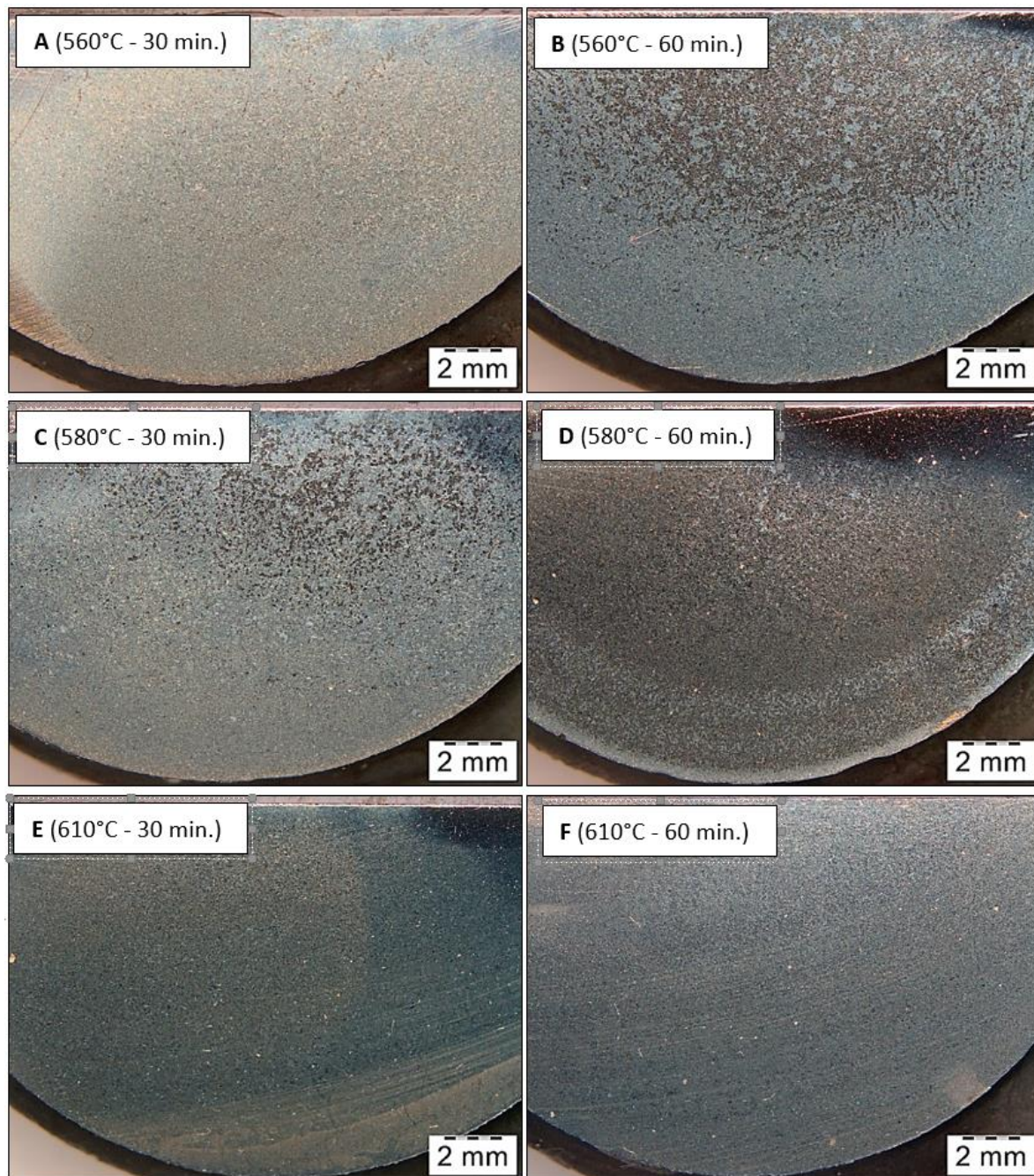


Fig. 8. Macroscopic images of samples annealed isothermally at the given temperatures

In order to precisely determine the formed phase components, a microstructural test was performed on an optical microscope as well as hardness tests by means of the Vickers method, according to the schematics presented in Fig. 9. On each sample, the microstructures of four areas were examined and 12 impressions were made.

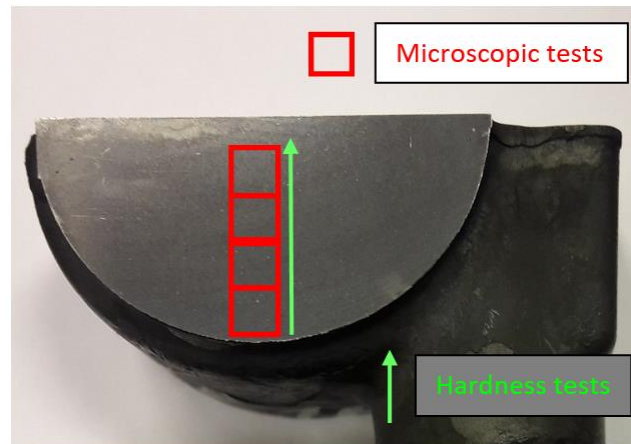


Fig. 9. A pictorial presentation of a sample used for microscopic and hardness tests. Marked areas of microscopic tests.

Fig. 10 shows the microstructure in selected areas for three temperatures and two treatment times. In the forgings annealed isothermally at 560-580°C, light-coloured areas of upper bainite as well as dark precipitations of pearlite with a small amount of martensite and bainite were recorded (Fig. 11). At 610°C, for times 30-60 minutes, we can observe an equilibrium structure – the EBSD tests demonstrated the presence of pearlite and a small amount of martensite. The martensite is the effect of the austenitic transformation, which was not complete. This transformation during the isothermal annealing is not finalized, which causes the presence of martensite.

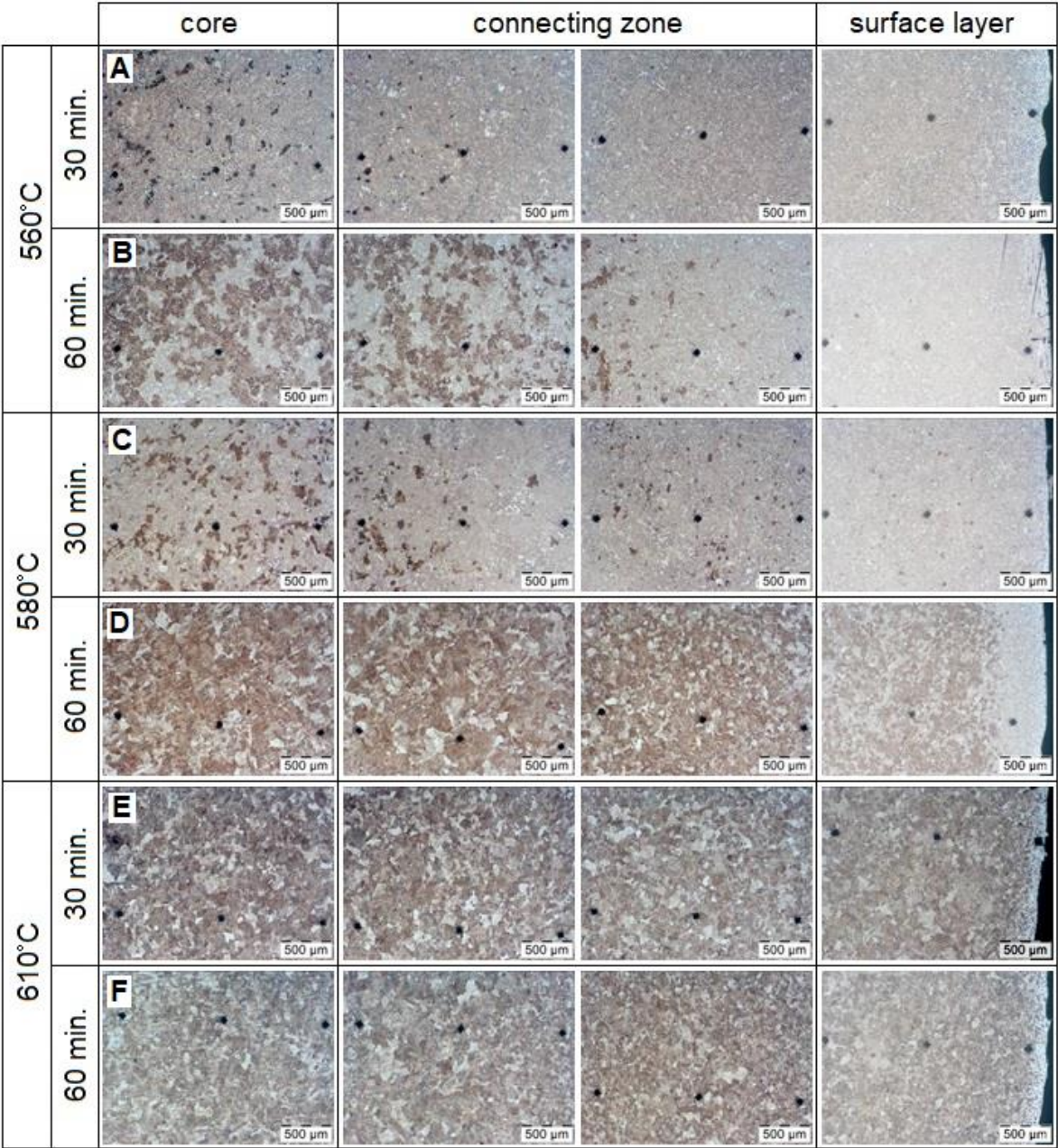


Fig. 10. Microstructure of isothermally annealed samples

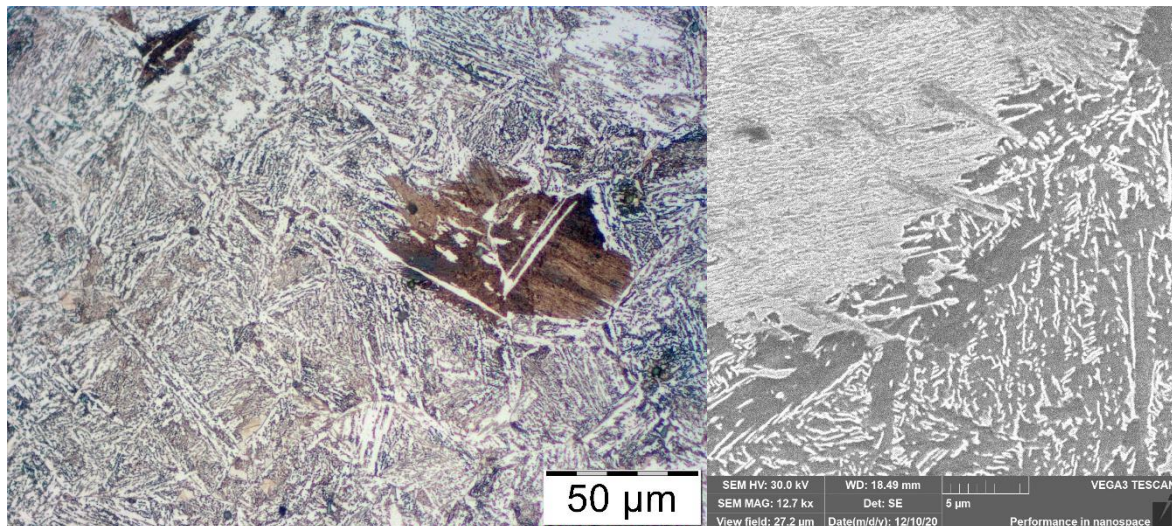


Fig. 11. Microstructural images of samples annealed isothermally at 560°C for 30 minutes taken on an optical and electron microscope

With the increase of the time of annealing in the furnace at the set-up temperature (560°C, 580°C, 610°C), the pearlite content in the volume of the material increases as well. For the temperature of 560°C, there is a trace amount of pearlite. For 580°C, a significant content of pearlite was observed, especially for the annealing time of 60 minutes. For samples isothermally annealed at 610°C, the pearlite constitutes practically the whole material volume. With higher magnifications (Fig. 12), we can observe a fine network of ferrite on the grain boundaries located in the core of the forging as well as interwoven cementite and ferrite plates in the pearlite.

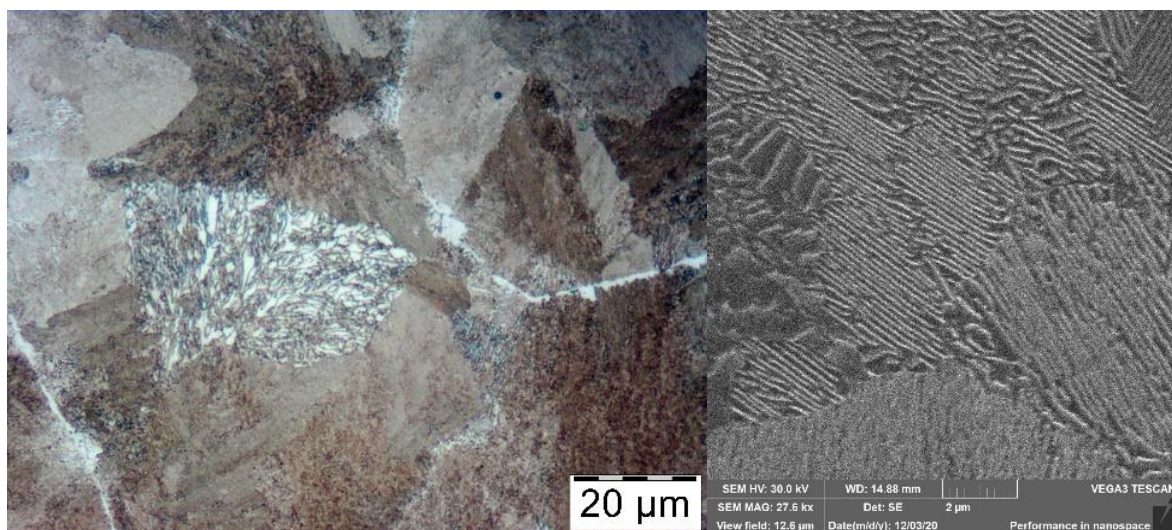


Fig. 12. Microstructural images of samples isothermally annealed at 610°C for 60 minutes taken on an optical and electron microscope

Such a distribution of phase components can be explained in the following way. Below a certain value, the lower the temperature of isothermal annealing, the longer the time needed for the transformation of austenite into pearlite. As it is a diffusive transformation, together with a decrease of temperature, the rate of its occurrence becomes lower as well [12]. If the transformation into pearlite is not complete and, after the forging is removed from the furnace, the cooled austenite remains, it will transform into bainite with a decrease in temperature. Despite the low rate of free cooling, the formation of bainite in this case is caused by the chromium and molybdenum additions present in this grade of steel [13].

The difference between the structure in the core of the forging and that at the surface results from the fact that the centre of the forging was cooled at a lower rate and after it was placed in the furnace, the core temperature was higher than at the surface. That is why the partial transformation of austenite

into pearlite could take place during a shorter time, before the temperature equalization took place. This is an important change in the case of an industrial application of such a thermo-mechanical treatment, as usually, isothermal annealing is carried out with the use of chamber furnaces, in which the forgings are arranged on trays. The heat exchange, with such a tight arrangement, between the centre and the surface of the forging is much slower, and so the temperature difference is small as well. This results in the formation of a more homogeneous structure within one forging. Also, the temperature from which the cooling begins is much lower, being in the scope of 30-50°C above Ac3. In turn, in the case of thermo-mechanical treatment, the starting temperature of cooling is determined by the temperature at which the forging process ends. The cooling rate in such a case cannot be too low, as this would cause an excessive grain growth, which would negatively affect the mechanical properties of the forgings. That is why, in series production, it is necessary to use a line with a regulated rate of air injection for controlled cooling.

Fig. 13 shows the results of microhardness tests performed on the examined cross-sections by means of the Vickers method with the load of 10 N. The black dashed line marks the scope of the required hardness, which, after recalculation, equals from 265 HV to 305 HV. For the samples annealed at 610°C for 1 hour, most of the measurement results are within the required range. The results for the remaining samples are usually above the required hardness, except for the measurements made right at the surface of the forging.

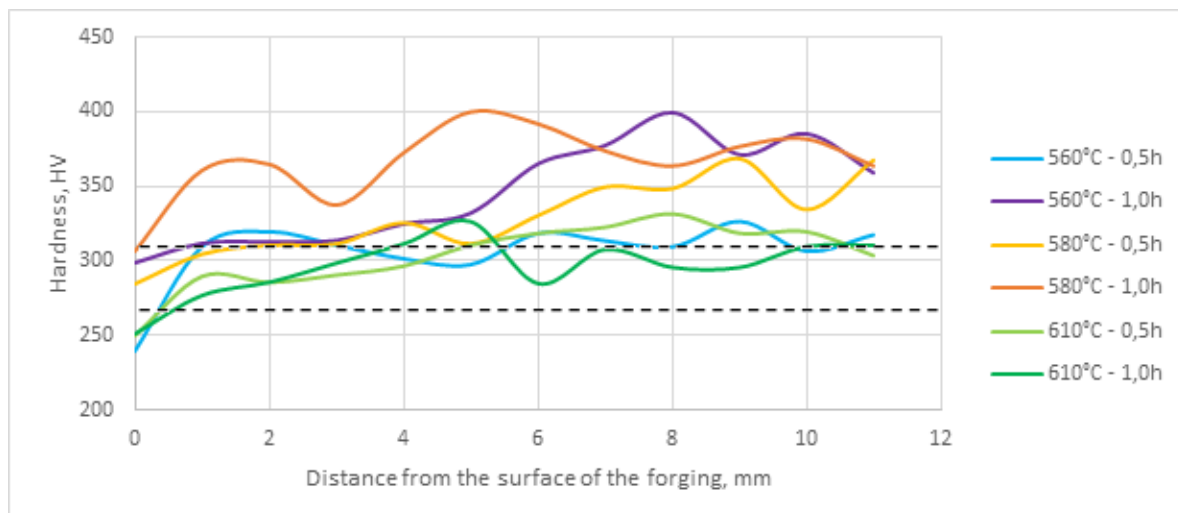


Fig. 13. Changes in hardness HV on a cross-section in the selected measurement plane for an isothermally annealed sample

During a measurement with such a small load, the result can be influenced by the particular phases of different hardness; and so, a measurement by the Brinell method was also made in the areas marked in Fig. 14. These are the measurement areas based on which the client accepts the forgings from the manufacturer.

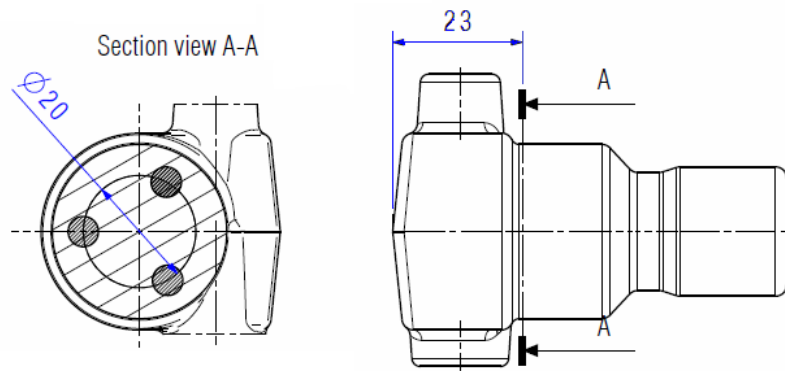


Fig. 14. Area of hardness impressions HB.

Only the sample annealed at 610°C for 60 minutes (Fig. 15) exhibits hardness in the required scope 249–280 HB. It should also be noted that the highest hardness was obtained by the forgings annealed at 580°C, not 560°C, as it could have been expected.

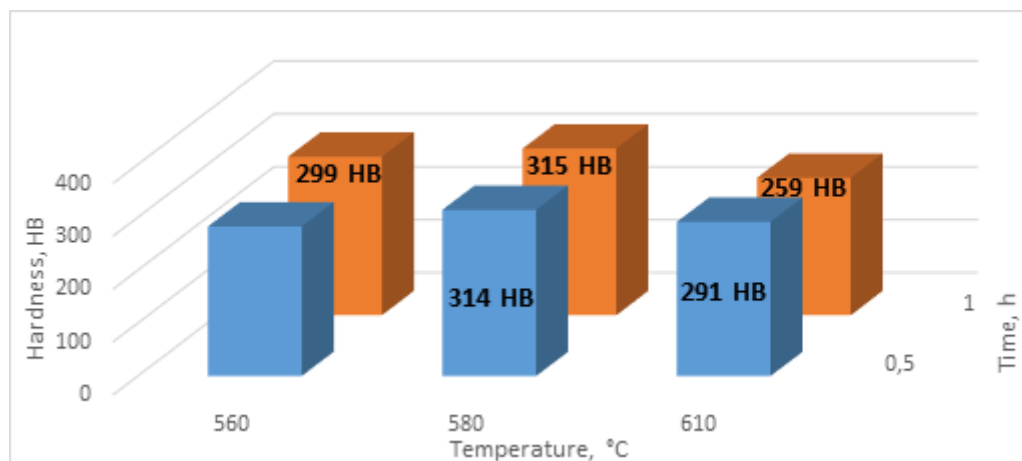


Fig. 15. Results of tests by means of the Brinell method of the mean hardness of forgings for different isothermal annealing times and temperatures

4. Comparison with thermal treatment used in series production.

The standard thermal treatment for forgings made of chromium-molybdenum steel consists of quenching and high-temperature tempering. After being annealed at 860°C, the forgings are rapidly cooled in oil to the ambient temperature (Fig. 16). Next, they are cleaned of the oil and heated at the tempering temperature. By measuring the hardness after the quenching, with a little bit of experience, it is possible to select such a temperature which makes it possible for the forgings, after tempering, to obtain hardness which is in agreement with the requirements. As, in such a case, it is not necessary to perform immediate tempering of the forgings, the former can be carried out on another station or in the same furnace after a certain time, necessary to change the temperature. Such a way of heat treatment ensures elasticity of production; however, it is connected with high energy consumption.

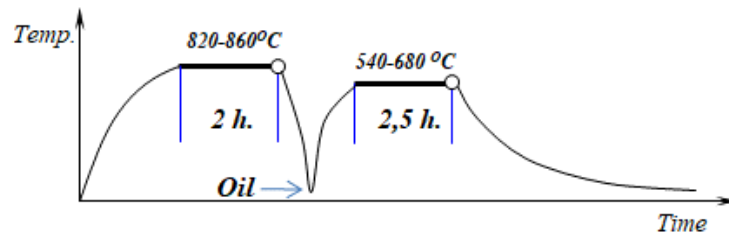


Fig. 16. Schematics of thermal treatment consisting of quenching in oil and high-temperature tempering, applied in series production of an adapter-forging

Fig. 17 shows the microstructure inside the forging observed under an optical and electron microscope. It is a typical microstructure of high-temperature tempered martensite. We can notice a fuzzy outline of a needle-shaped structure consolidated by the cementite precipitations. With a higher magnification, we can see very fine rounded cementite particles in a ferritic matrix, which the high-temperature tempered martensite consists of.

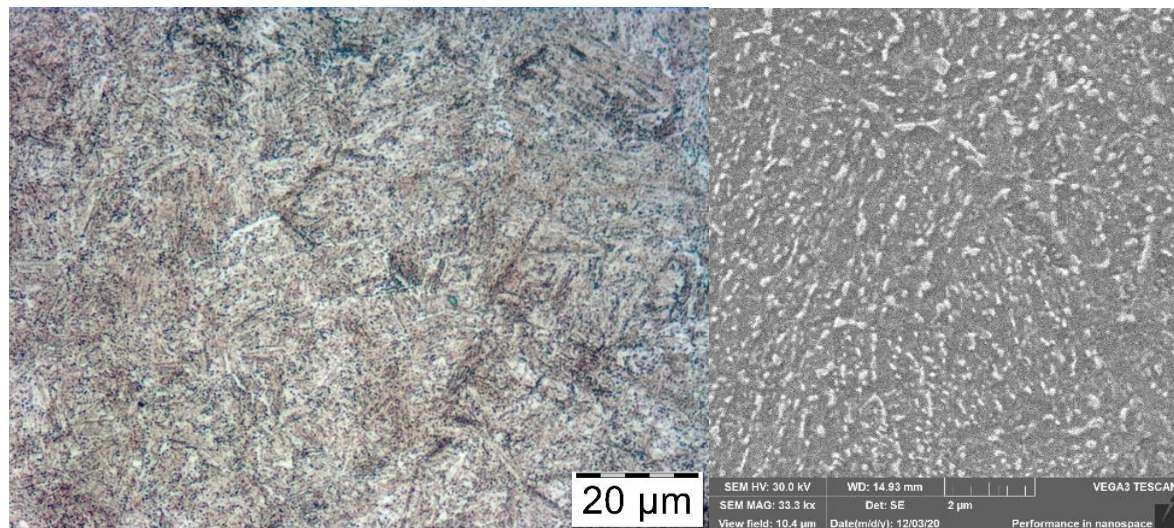


Fig. 17. Microstructure images of a forging quenched in oil and then tempered taken with an optical and electron microscope

Analogically to the previous samples, in this case also, microhardness tests by means of the Vickers method were made with the load of 10 N (Fig. 18). It can be inferred from the diagram that most of the measurement points are within the required hardness scope. In order to verify whether the forging meets the requirements, a hardness test by the Brinell method was also performed according to the client requirements described earlier. The measurement results confirmed that the examined forging had obtained hardness 275 HB, and so it was within the required scope 249–280 HB.

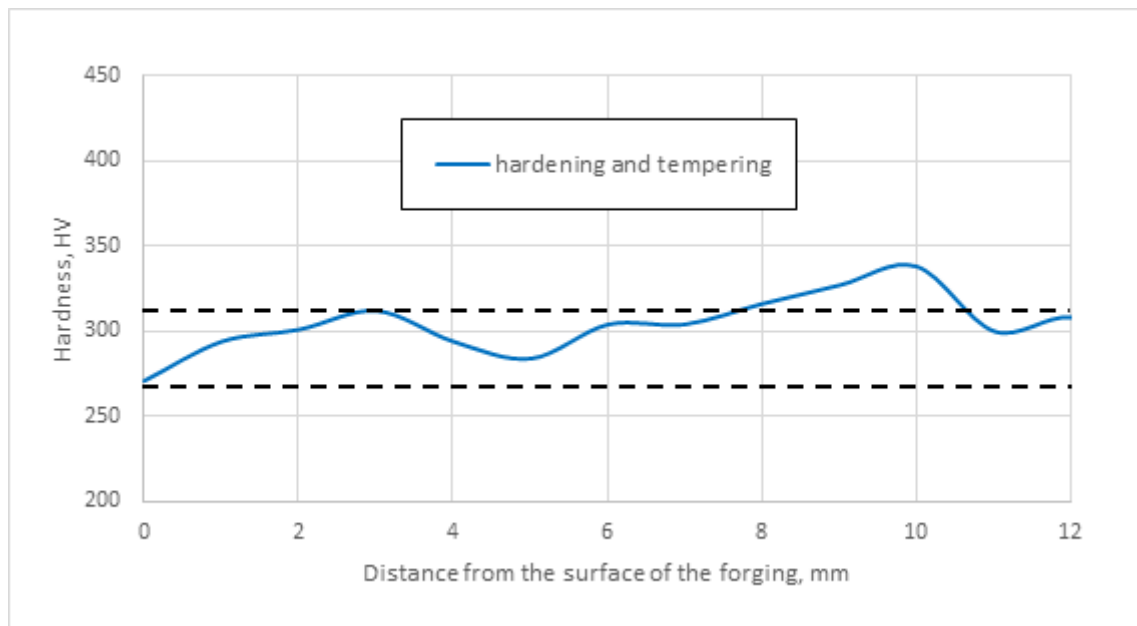


Fig. 18. Changes in hardness HV on the cross-section in the selected measurement plane for a forging quenched in oil and tempered

For a more accurate comparison of the mechanical properties, plastometric examinations were also performed on samples cut out of the forging. The results suggest that the reinforcement curves run very similarly (Fig. 19), both for the forgings isothermally annealed directly after the forging process and those from a series production subjected to quenching with high-temperature tempering. In this case, the presented samples come from the forging which was previously qualified as the one best meeting the requirements, that is the one annealed at 610°C for 60 minutes. The maximal real stresses, before the sample had been destroyed, reached values in the scope from 1050 MPa to 1100 MPa for both forgings.

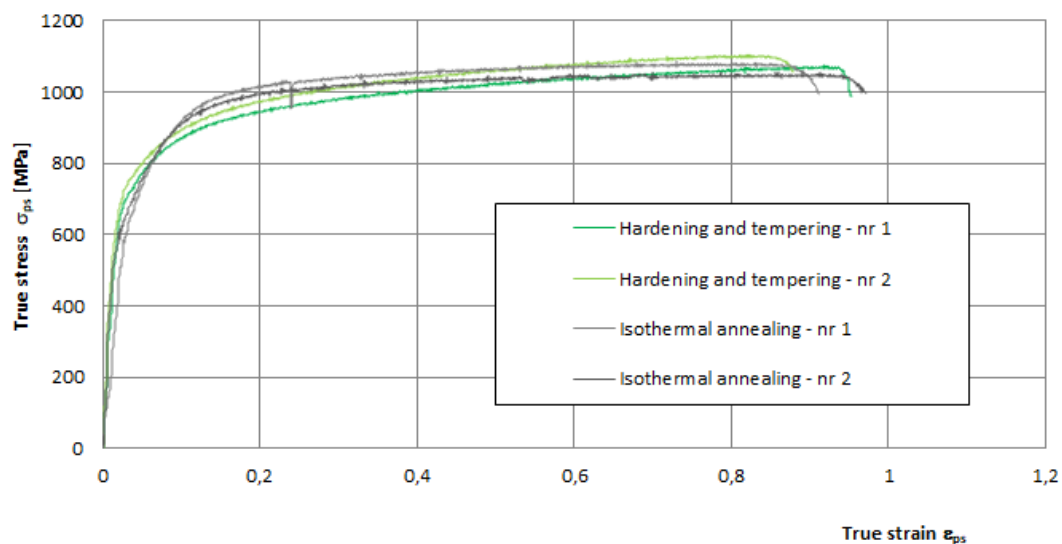


Fig. 19. The stress-strain curve of the samples cut out of a forging quenched and tempered and a forging isothermally annealed at 610°C for 60 minutes

5. Discussion and conclusions

We can infer from the performed investigations that applying heat treatment directly from the forging temperature makes it possible to obtain the correct properties of the forgings, comparable with the standard thermal treatment. Comparing the results between the proposed technology and the current production process, it can be stated that they fulfill the expectations of the recipient. Despite the

formation of a ferritic-pearlitic microstructure, the obtained hardness of the forging was comparable with the hardness after the process of quenching and high-temperature tempering. Owing to this, the subsequent machining will be easier and less labour consuming. Also the stress-strain curves illustrate a similar behaviour of the forging collected from the series production process and the one isothermally annealed right after the forging.

On the example of isothermal annealing, we can see that, beside the temperature, the time during which the process takes place is important as well. This can cause certain difficulties in industrial applications, as the isothermal annealing time is limited by the length and the minimal speed of the line. Moreover, isothermal annealing is a continuous process, in which there is no possibility to verify the effects during its course. This constitutes a significant difference in respect of quenching and tempering, where, based on the hardness measurements of the forgings after quenching, it is possible to select the tempering temperature with high accuracy. That is why it is so important to properly determine the parameters of the process before it begins.

The described technology of heat treatment has also its disadvantages. One of them is the necessity to invest into a new heat treatment line with high efficiency, similar to that of the forging process. What is more, the line has to be located right next to the forging or trimming press. With such a production arrangement, it is impossible to introduce corrections to the forgings, and so, before the start-up of a series production, it is necessary to collect experimental data for different heats of the same grade. The data collected during the research will provide the possibility to create an industrial technology of thermo-mechanical treatment of forgings with the use of the forging heat, which will allow a significant energy saving.

Author Contributions:

Funding: The research has been financed by the National Centre for Research and Development, Poland, from the project TECHMATSTRATEG1/348491/10/NCBR/2017: „Energy saving technology of thermo-mechanical treatment of forgings with the use of the forging heat”.

Conflicts of Interest: The authors declare no conflict of interest.

References

- [1] Readt H. W. *MassivumgeformteKomponenten*. Hirschvogel Holding, 2014.
- [2] Szyndler R. Stan i perspektywy rozwoju branży kuźniczej. *Hutnik – Wiadomości Hutnicze*. 3, 2000, 111-114.
- [3] Skubisz P. and Żak A. Technologie i urządzenia stosowane do obróbki cieplnej odkuwek matrycowych bezpośrednio po kuciu. *STAL Metale & Nowe Technologie*. 9-10, 2015, 66-70.
- [4] Pidvysots'kyi V., Opara J., Wrożyna A., Zalecki W., Kuziak R., Simulation of Thermo-Mechanical Processes During hot Forging and Prediction of Mechanical properties of Products, Committee of Metallurgy of the Polish Academy of Sciences, Kraków, Poland, 2011, 229-236.
- [5] Skubisz P., Żak A., Burdek M., Lisiecki Ł., Micek P., Design of Controlled Processing Conditions for Drop Forgings Made of Microalloy Steel Grades for Mining Industry. *Archives of Metallurgy and Materials*. 60, 2015, 445-453.
- [6] Karmakar A., Mukherjee S., Kundu S. Effect of composition and isothermal holding temperature on the precipitation hardening in vanadium-microalloyed steels. *Materials Characterization*. 132, 2017, 31-40.
- [7] Opiela M. Obróbka cieplno-plastyczna odkuwek ze stali mikrostopowych. *STAL Metale & Nowe Technologie*. 11-12, 2017, 34-39.
- [8] Javaheri V., Khodaie N., Kaijalainen A., Porter D., Effect of niobium and phase transformation temperature on the microstructure and texture of a novel 0.40% C thermomechanically processed steel. *Materials Characterization*. 142, 2018, 295-308.
- [9] Biradar A., Rasiwasia R., Soni J., Orłowska M., Rijesh M., Thermomechanical roll bonding of Al-6063

- strips. *Journal of Alloys and Compounds*. 855, 2020, 1-7
- [10] Naylor D.J. Review of international activity on microalloyed engineering steels. *Ironmaking and Steelmaking*. 16, 1989, 246–252.
- [11] Zwierzchowski M. Analysis of the possibilities of using forging heat in isothermal annealing processes for AISI 4140 alloy. *Archives of Metallurgy and Materials*. 65, 2020, 951-958.
- [12] Dobrzański L. A. *Podstawy nauki o materiałach i metaloznawstwo*. Wydawnictwo Naukowo-Techniczne, 2012
- [13] Colpaert H. *Metallography of Steels: Interpretation of Structure and the Effects of Processing*. ASM International, 2018