

Z. GRONOSTAJSKI<sup>1</sup>, M. HAWRYLUK<sup>1\*</sup>, P. JABŁOŃSKI<sup>1</sup>, M. ZWIERZCHOWSKI<sup>1</sup>,  
A. BARELKOWSKI<sup>1</sup>, P. WIDOMSKI<sup>1</sup>

## THE EFFECT OF HEAT TREATMENT OF FORGINGS DIRECTLY FROM THE FORGING TEMPERATURE ON THEIR PROPERTIES

The paper presents a prototype semi-industrial cooling line developed by the authors, which makes it possible to design a thermal treatment of forgings with the use of the forging heat, together with exemplary test results for forgings forked type. The proposed method of heat treatment dedicated to these forgings was described and compared to traditionally used heat treatment method in chamber furnaces. Next, the original research stand was presented, which performs mechanical fatigue test on final products – forked-type forgings. Forgings after heat treatment and cooling on the prototype line were tested on this stand in condition of cyclically variable mechanical loads in order to resistance to mechanical fatigue was analyzed and the influence of performed exemplary heat treatment on mechanical properties. The presented preliminary investigations performed on the designed combined research standing, consisting of: the prototype controlled cooling line, as well as mechanical fatigue stand point to the possibility of implementing thermal treatment with the use of the heat generated during the forging process and determining its impact on the mechanical properties of forgings.

*Keywords:* heat treatment; hot die forging; controlled cooling line; thermo-plastic treatment technology; mechanical properties of forging

### 1. Introduction

Currently, in addition to achieving the assumed geometry of the forged product, forgings should be characterized by specific properties specified by the customer, which are most often obtained by heat treatment. As the mechanical properties are inherited from the microstructure, it is necessary to well recognize this relation. Depending on the expectations with regard to the product, such as the chemical composition of the forging or its shape, the processes of annealing, hardening and tempering as well as oversaturation and ageing are implemented. The thermal treatment of die forgings is generally realized after the process of forging and trimming in order to unify the microstructure and properties of the forgings. It mean, that can be realized after cooling from the forging temperature to the ambient temperature and then re-heating [1-3]. However, attempts are also being made combining the plastic strain process with the thermal treatment have been made, which, in many cases, provided a synergistic combination of the effects of the dynamic processes related to hot deformation with the effects of the diffusion transformations. A direct combination of this type makes it possible to obtain

mechanical properties which sometimes exceed those possible to obtain through hot forging and thermal treatment performed separately. Thermo-plastic treatment consists in changing the mechanical properties of metals in the solid state by inducing structural changes in them, which are an effect of the combined operation of the temperature, time and plastic deformations (joined thermal and plastic treatment processes) [4].

A typical cycle of conventional heat treatment of die forgings includes: heating the input material to the initial forging temperature, i.e. approximately 1100°C-1300°C, multi-stage forging on a selected forging aggregate. Forgings after the forging process have a temperature of about 1100°C and, depending on the technology, they can be trimmed on hot (possibly after cold cooling); then they are cooled in a box or sometimes on a controlled B-Y cooling line to ambient temperature. They are then re-heated for normalization and cooled in the air or heated to the austenization temperature and cooled in oil, water or other medium. Sometimes tempering is also used [5-9].

Based on the description provided, it can be concluded that obtaining high strength forgings as well as plasticity in the forging process and conventional heat treatment requires many ad-

<sup>1</sup> WROCLAW UNIVERSITY OF SCIENCE AND TECHNOLOGY, METAL FORMING, WELDING AND METROLOGY, 5 LUKASIEWICZA STR., 50-371 WROCLAW, POLNAD

\* Corresponding author: marek.hawryluk@pwr.edu.pl



ditional heating operations within the given heat treatment [10]. And this is related to the extended production cycle and the accompanying additional costs of labor, operation of equipment, refrigerants, and above all the energy necessary for repeated heating. Therefore, one of the alternatives has become thermoplastic machining, which uses the heat generated by the forging process, which consequently eliminates the need to cool forgings after the forging process to ambient temperature and reheat them. Instead, by appropriate selection of parameters on a controlled cooling line, a given thermal treatment can be started almost immediately after the forging process [11-16]. The use of thermoplastic processing technology requires the development of know-how combining knowledge in the field of phase change kinetics during and after deformation with the technical possibilities of its application in industrial conditions. Therefore, research conducted in this field is fully justified, because for obvious reasons they will bring many benefits, both scientifically and financially. In the literature you can find many items and studies related to investigations are performed on the use of thermo-plastic treatment, which compare the obtained properties as well as the economy of the process with the traditional methods [16-18]. In work [19] compares the mechanical properties of metal sheets with a ferritic-martensitic structure made of steel C-Mn with micro-additions Nb and Ti produced by means of an energy saving thermo-plastic treatment technology, with those obtained after the conventional hardening from a temperature above AC1. The research was also confirmed in the study [20] which presents the effect of thermo-plastic treatment through forging on the structure and properties of micro-alloy steel. The forgings produced by the thermo-plastic method underwent tempering within the temperature range of 550°C to 650°C. As a result, the properties at the level of: Rp0,2 – from 993 to 925 MPa, Rm – from 1061 to 978 MPa and KV-40 from 60 to 69J were obtained. In turn, the work [21] examines the effect of different thermal treatment parameters on the mechanical properties of a steam turbine blade, which works at the temperature of about 700°C. Also with the development of new grades of steel, thermo-plastic treatment is more and more frequently applied. In study [22] demonstrates that, with the use of thermo-plastic treatment, it is possible to obtain mechanical properties of Fe-C-Al-based alloys not containing critical elements which are comparable to those of the traditional alloys. The use of thermo-plastic treatment is also applied for other alloys based on Ti [23] and Al [24]. In addition, many interesting papers can be found in the literature in which the authors examined various aspects of thermo-plastic both using numerical modeling [25] regarding microstructural changes after different variants of such treatment [26] as well as the impact of changes in heating / cooling parameters immediately after forging on the mechanical properties of forgings, including for the aviation industry [27-29]. The above presented studies indicate research-based confirmation of the economical and mechanical advantages of the thermoplastic technology.

It should also be mentioned that heat and thermo-plastic treatment carries numerous undesirable consequences with it, in the form of, e.g.: non-uniform distribution of structure, ori-

ented banding of grains, and in consequence, also non-uniform distribution of the material's properties throughout the forging's entire volume. Additionally, the presence of the material at high temperature causes the formation of the oxide layer on the surface of the material, leading to accelerated corrosion. Residual stresses remaining after processing, resulting from thermal shocks, may initiate cracks during exploitation of the product, and as a result of diffusion of alloying elements at elevated temperature, there is a risk of decarburization of the piece's surface layer. To counteract this, heating rates are changed, and the target and amount of heat emitted through induction heating is regulated in hardening and tempering processes, where induction heating can be applied to obtain a precisely defined final hardness of the material. The fatigue strength of forgings can be a measure of quality of the performed heat treatment and of the microstructure obtained thereby. This is typical, particularly in the case of forked-type forgings, whose method of work can be described as fatigue-based and loads during exploitation as periodically variable. The factors that may affect the fatigue strength of forged products are surface roughness, microstructure, hardness and residual stresses. Heat treatment may influence these factors, particularly in the surface layer of the forging's material, and reduce fatigue strength. To limit the effect of changes in the surface layer occurring during heat treatment on fatigue strength, deformed products undergo finishing, usually by means of mechanical methods.

**The main goal of paper is presented the preliminary test results obtained from developed a prototype semi-industrial cooling line and compare different methods of heat treatment of the same type of forging for the purpose of verifying the effectiveness of the treatment and its influence on the selected mechanical properties, like: hardness and fatigue strength of parts. Experimental tests performed on a test stand designed especially for this purpose made it possible to determine the number of cycles resulting in permanent deformation or total failure of a forgings and maximum torsional moment and the evolution of its changes as a function of time.**

## 2. Industrial forging process with selected toughening variants

Fig. 1 shows an exemplary "traditional" forging production cycle followed by the thermal treatments of the forgings. As we can notice, in the case of the selected typical yoke-type forging production process, the forging is followed by controlled cooling of the forgings on the controlled cooling line, where, at the end of this operation, after the forging falls into the box, its temperature is about 600°C (close to the transformation temperature for that material). Next, the forgings, after reaching the ambient temperature in the container, are collected in a storage area and then subjected to shot blasting and toughening. We should point to the duration of the whole production cycle and the fact that the forgings are twice re-heated, which, as it was mentioned before, is connected with a higher consumption of energy as

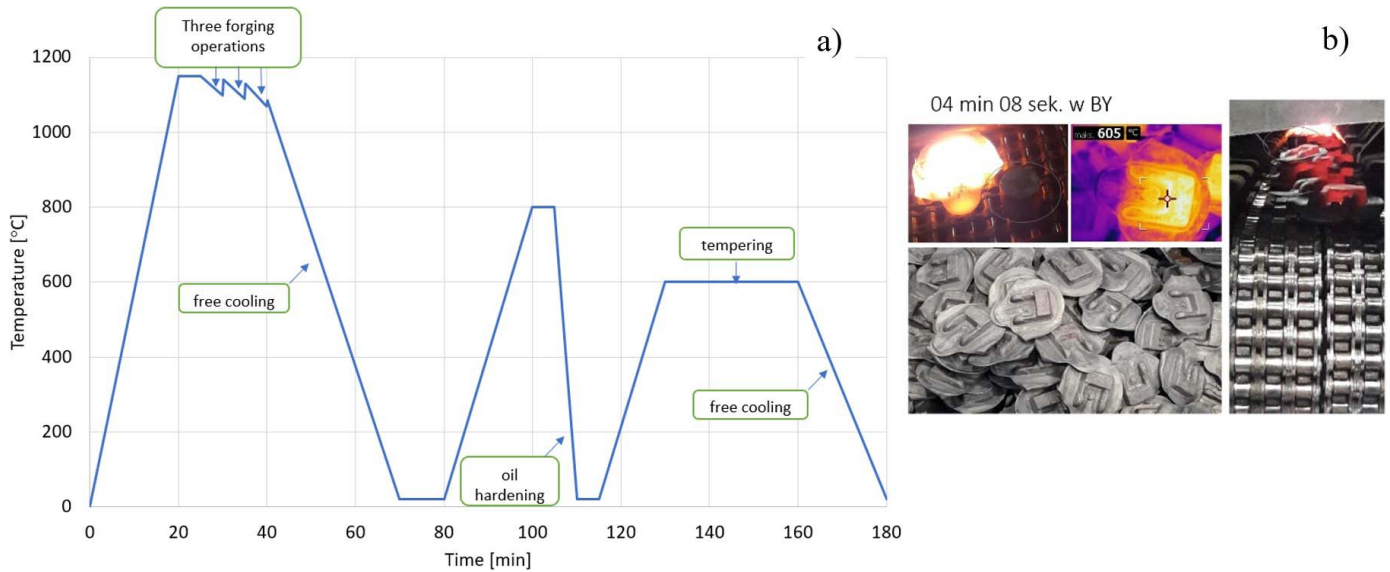


Fig. 1. The view of: a) an example of a forging production cycle with a separate turnover heat, b) pictures of forgings during and after controlled cooling

well as cooling agents. For this reason, within the performed research, a decision was made to use the heat generated by the forging process and to perform three different variants of thermal treatment directly after the end of the third forging operation.

Fig. 2 shows the schematics of the performed investigations for: hardening directly from the forging process (the course marked in blue), hardening after the forging with annealing at 870°C (the course marked in gray) and cooling from the forging temperature down to 600°C (temperature below the perlitic transformation), heating and annealing at 870°C, followed by hardening (the course marked in orange). Also, for all the three variants, after hardening, the process of tempering was performed (according to the technology designed for this product). The assumed levels and temperatures were determined by the analyzed material, i.e. steel C45, as well as the performed research. For this steel, the pearlitic transformation with free cooling takes

place at about 670°C (that is why the forgings were cooled down to 600°C), whereas the austenitization temperature is about 860°C-880°C.

Examinations of the microstructure as well as hardness tests for the analyzed yoke-type forgings were performed. The hardness tests were carried out by means of the Vickers method with the load of 10N (1kg) as well as by the Brinell method. The samples were etched in 3,5% Nital. The obtained results of the microstructural tests have been shown in Fig 3. Hardening directly from the forging temperature is possible to perform but, from the technological point of view, it is unjustifiable. The generated high hardening stresses may cause deformation of the product and/or its cracking during the cooling process. For I technology (Fig. 3a), we can observe a structure of tempered martensite with numerous fine precipitates of  $Fe_3C$  in a globular form.

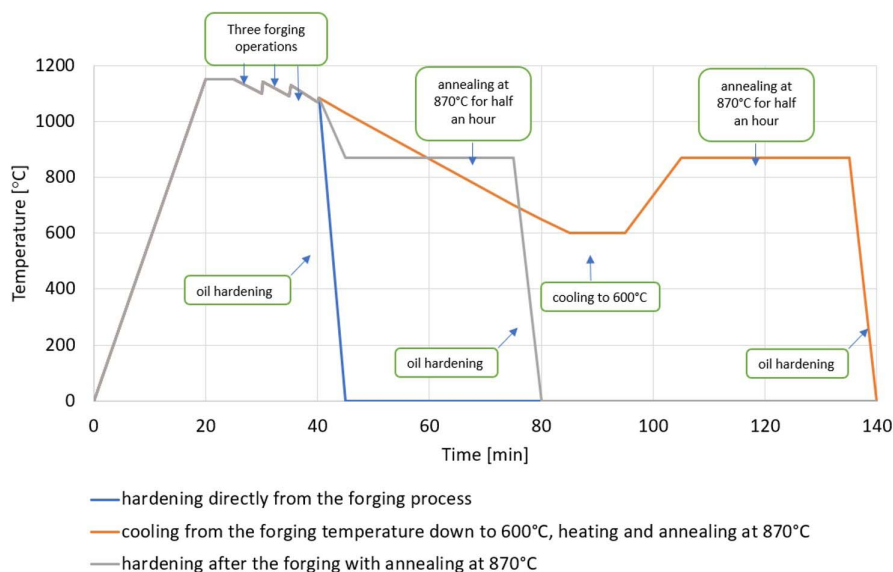


Fig. 2. Schematics of the proposed thermal treatment variants after the forging process



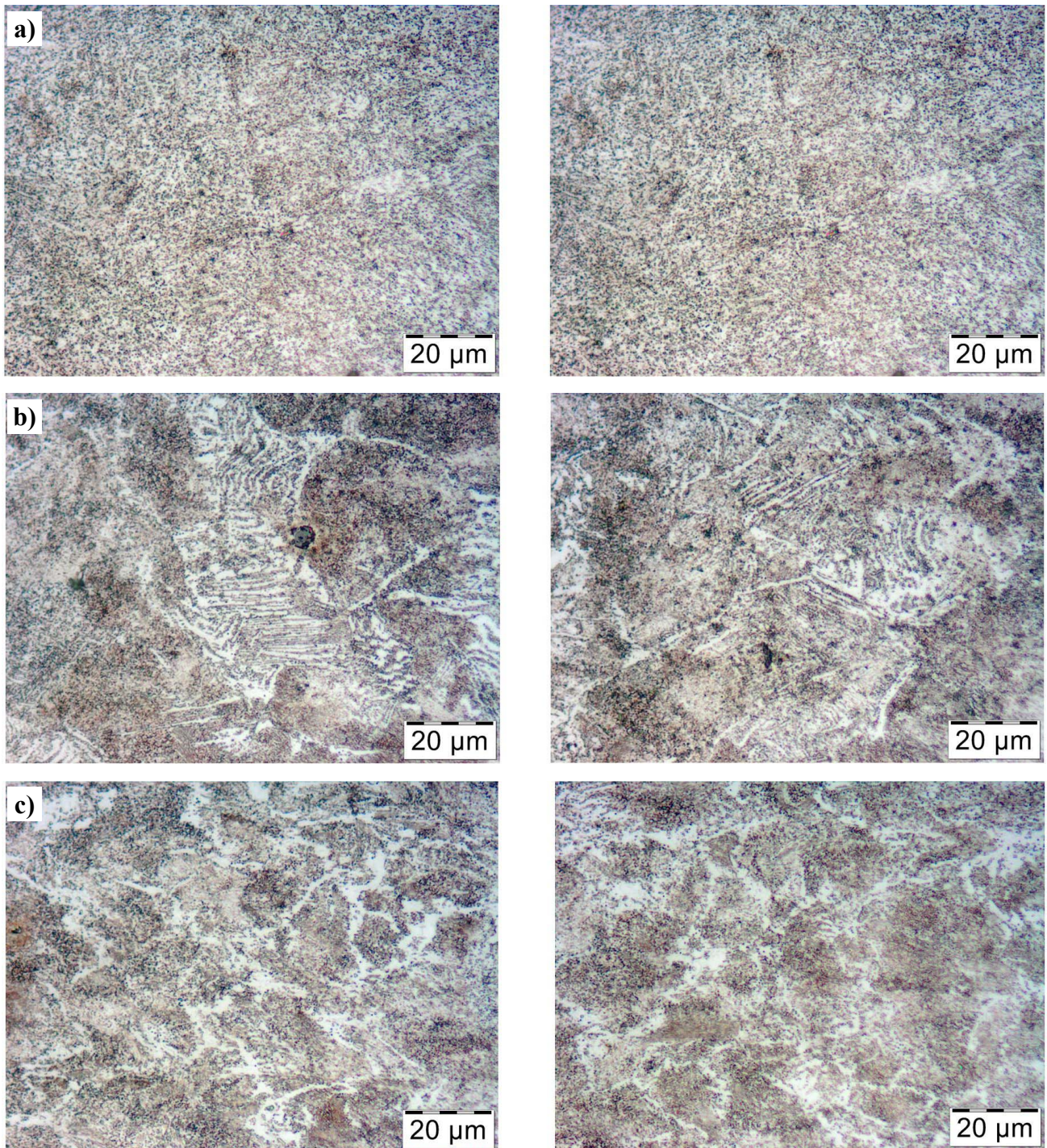


Fig. 3. Microstructural test results after toughening for three hardening variants: a) technology I, technology II, c) technology III

Relatively long martensite needles and no ferrite lattice on the grain boundaries of the former austenite. The microstructure of the forgings made according to II technology significantly differs from that of first technology. Visible ferrite precipitations on the boundaries of the former austenite grains (Fig. 3b) and apart from that, a typical sorbitic structure after the toughening procedure. The microstructure of the forgings made according to variant 3 also exhibits ferrite precipitations on the former austenite grain boundaries (about 30-50  $\mu\text{m}$  – Fig. 3c). Additionally, fine  $\text{Fe}_3\text{C}$  precipitations in a globular form. The results obtained from the procedure of toughening of a yoke-type forging made

of steel C45 (microstructure, hardness) with the presented time-temperature parameters confirm its agreement with the expectations on the operation sheet of the end recipient. Depending on the recipient's expectations, by changing the parameters of the thermal treatment, we can regulate the properties of the ready product.

Fig. 4 shows the results of the microstructural tests for the 3 selected thermal treatment technology performed directly after the forging process, from the forging heat. The final mechanical properties of the product are determined by the tempering temperature as well as the hardening parameters.



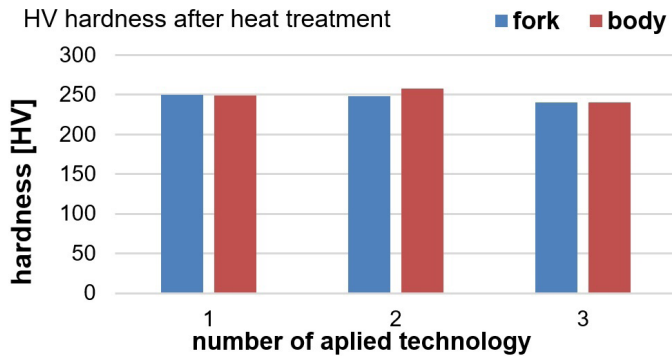


Fig. 4. Microstructural test results for the 3 selected thermal treatment variants – thermal improvement

As it can be observed based on the obtained results, regardless of the applied thermal treatment variant, the hardness value is within the scope of 230-260 HV, which is also in agreement with the requirements on the technological sheet. On this basis, we can establish that performing the thermal treatment procedures directly from the forging process has not negative effect either on the microstructure or the hardness of the forgings obtained after the thermal treatment. What is more, we can draw the obvious conclusion that it is economically justified, both from the point of view of the process efficiency and the production costs, to carry out the thermal treatment process directly from the forging temperature. In this case, it is crucial to determine the times and rates of cooling, that is to ensure high regime temperature control. As it was demonstrated in the subject matter section, the current trends suggest that, in the economically developed countries, in order to eliminate the time and energy consuming thermal treatment procedures, in the case of the use of precipitate strengthened microscopic steels (about 60% of the current production), it is required that regulated cooling after the forging process be performed.

### 3. A prototype experimental line for the production of forgings with the use of the forging heat

In order to analyze the effect of the selected parameters on the thermal treatment of forgings, the authors constructed a prototype experimental line for the implementation of different thermal treatment variants, based on high temperature thermo-plastic treatment enabling a simulation and optimization of the

thermal treatment process performed under industrial conditions. On the basis of the obtained results on this experimental line, an industrial line will be constructed, which will make it possible to perform thermal treatment under industrial conditions.

The idea of such a line is based on a random arrangement of the four crucial devices: a screw press for hot forging (P), a controlled cooling line (L), a furnace to heat the charge and the forgings (F) and a quenching tank (Q). This way, it is possible to perform thermo-plastic treatment in any configuration, that is, it enables both normalization and toughening (Fig. 5a). With such a selection of devices, it is possible to simulate almost any thermal treatment process (Fig. 5b).

A novelty in the proposed solution is a prototype line of controlled cooling. It consists of a chamber, 3 m long and 0,5 m wide, with a belt conveyor, on which the heated material is placed. Above the chamber, four ventilators are located, each with the power of 600 W, which pump the air into the chamber in order to cool the examined material. The speed of the ventilators and the tape feed is regulated by means of frequency converters. Owing to the use of a high velocity ratio, it is possible to fully load the line with the weight of up to 150 kg/m. The side walls of the chamber were designed in such a way so that the biggest possible stream of air would flow around the forgings moving on the belt. An important aspect was such a construction design which would make it possible for the forging to be cooled uniformly on each side, including the bottom. For this reason, a conveyor belt made of a heat-resisting net with big meshes was used, which minimized the air resistance and reduced the ground effect.

#### 4.1. Exemplary tests under semi-industrial conditions

In order to perform preliminary tests on a semi-industrial stand for the verification of the developed controlled cooling line, the C45 grade charge material was used. Measurements on samples with the dimensions of  $\varnothing 35 \times 20$  and  $\varnothing 35 \times 40$  were carried out. For each material of the given dimension, 12 identical samples were prepared. On each sample, a single heating followed but controlled cooling test was performed. Such a procedure was implemented due to the possibility of the presence of scale in the case of repeated heating of the same element, which may significantly slow down the cooling process. Each test consisted in heating the material in a heating furnace to a temperature

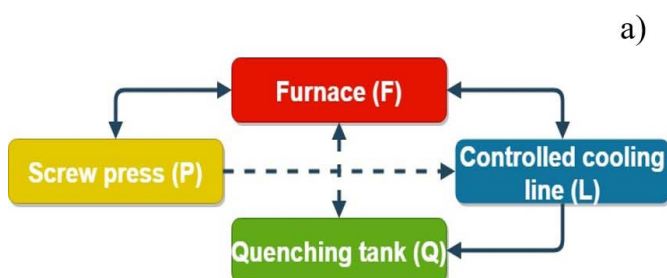


Fig. 5. a) A block diagram of the test stand for thermo-plastic treatment, b) exemplary arrangement of the test stand for thermo-plastic treatment

above 1100°C, and next subject it to a process of controlled cooling to 400°C on the test stand. For each examined sample from the given series, a different speed of the ventilators was applied – changed by 5 Hz by means of a frequency converter in the range from 0 Hz (0 rpm) for the controlled cooling to 55 Hz (1650 rpm) for the maximal ventilator speed. The speed of the tape feed for all the measurements was constant, at the level of 5 Hz, which gives the speed of about 1,8m/min. Changing the tape feed speed has no effect on the speed of the sample's cooling. During each process, the temperature in the geometrical centre of the sample was recorded by means of a sheathed thermocouple type K with the diameter of 1,5 mm. After each test, the cooling time was measured by way of measuring the difference between the time when the temperature of 1100°C was reached during the cooling and the time when the temperature of 400°C was achieved. The cooling courses for C45 steel have been shown in a diagram (Fig. 6).

During the cooling process, we can observe a changing temperature of the beginning of the phase transformation of austenite into pearlite, depending on the cooling rate. For the material C45, the boundary is more visible because of a higher

carbon content and the lack of alloy elements, which could cause the formation of other phases, such as bainite or martensite, with a significantly lower heat release. In order to optimize the time of the thermal treatment, which is important from the point of view of the production time, based on the collected data and the measured cooling time of the sample from 1100°C to 400°C, a dependence of the cooling time on the ventilator speed was built for analyzed material C45 steel and to compare with 16MnCr5. For example, the characteristics for the sample  $\varnothing 35 \times 20$  and  $\varnothing 35 \times 40$  C45 (Fig. 7 – blue line) were determined on the basis of the times measured for a series of 12 such samples, with different speeds of the ventilators (Fig. 6), and also for second material 16MnCr5 for geometry  $\varnothing 35 \times 20, 40, 60$  mm of length.

Having such a compilation at one's disposal, it is possible to notice that, despite the different materials applied, the cooling times for the same geometrical parameters of the samples are similar (Fig. 7). It should be noted that for steel 16MnCr5 during determining the cooling curves at different speeds, the cooling curves with different speed change was not as visible as the C45. The difference is caused by e.g. the differences in the thermal emissivity of the materials, the formation of scale, etc.

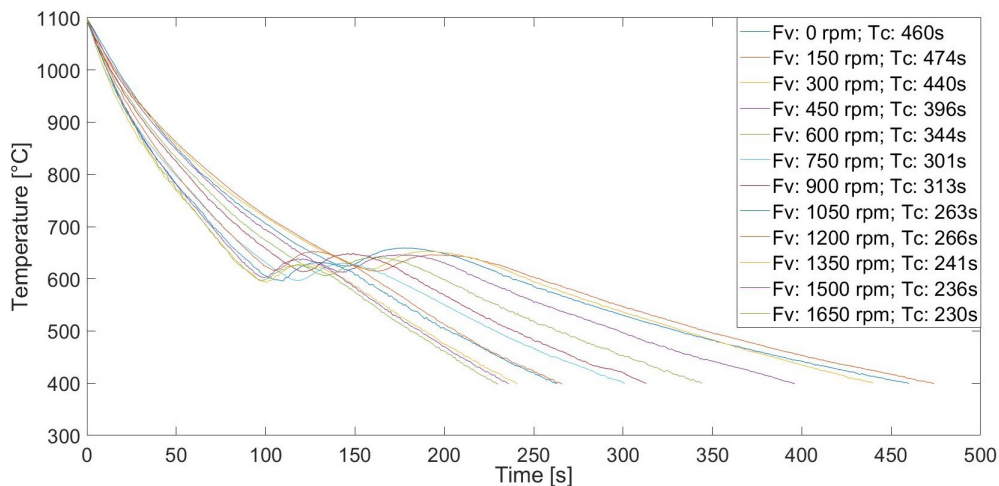


Fig. 6. Cooling course of a C45  $\varnothing 35 \times 20$  bar within the scope of 1100°C-400°C

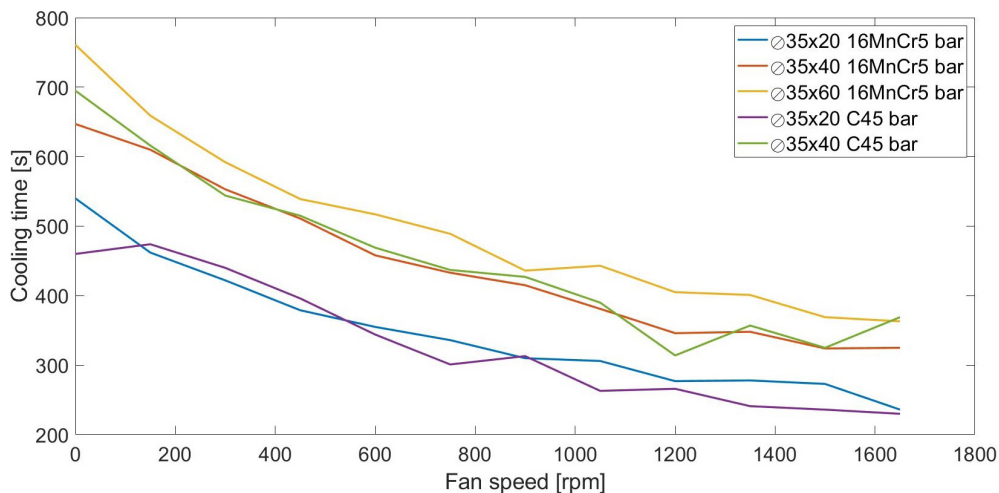


Fig. 7. Cooling course of 16MnCr5 and C45 bars with the dimensions  $\varnothing 35 \times 20$ ,  $\varnothing 35 \times 40$  and  $\varnothing 35 \times 60$ , within the scope of 1100°C-400°C, in the function of the ventilator speed

We can also see that the courses are parallel, regardless of the internal dimension or the volume of the examined element. The slight differences between the consecutive measurements can be caused by a non-uniform formation of scale on the surface of the samples and the related heat removal.

#### 4.2. Preliminary tests on a yoke-type forging used in steering gears of motor cars

The first stage in the application of the results obtained from the controlled cooling line was to perform cooling for the selected yoke-type forging made from the material C45, which is commonly applied in the motorcar industry as an element of the steering gear. In the first place, as the reference point, the curves of cooling during the industrial process, on the industrial controlled cooling line B-Y, were determined. In turn, on the developed research line, the cooling curves for those samples were determined in the case of the maximal ventilator speed for two variants – cooling of a single forging and cooling of a forging placed between heated forgings (Fig. 8). The aim of this was to verify how much longer the cooling time would become in the case of the forging placed between other forgings, where an additional heat source is present, as all the previous tests on the line had been performed on single forgings. During each process, the temperature in the geometrical centre of the back part of the sample as well as inside one of its arms was being recorded by means of sheathed thermocouples type K with the diameter of 1,5mm. Such a measurement was realized due to significant dimensional differences of the element (difference in shape and volume).

In the case of cooling on the industrial line from the forging temperature to 400°C, this time equals 631s, whereas in the case of cooling on the developed prototype line, with the maximal ventilator efficiency, that time was reduced by a half. The difference between the measurement points (the fork and the body) equals about 50°C, whereas the cooling time to 400°C for the forging placed between others forgings increased in respect of the single forging by about 80s.

As it can be seen, on the constructed controlled cooling line, which constitutes a crucial part of the test stand used for the development of a thermal treatment technology taking advantage of the forging heat, it is possible to simulate almost any conditions, including those which could be present under industrial conditions, in die forges. The obtained test results referring to the cooling times and rates were applied to design and construct an industrial controlled cooling line as part of the project TECHMATSTRATEG1/348491/10/NCBR/2017. The line is currently being assembled and activated, and in the nearest future, the first tests are to begin and a verification of its proper operation, according to the assumptions, on the developed prototype laboratory cooling line will be performed.

#### 4.3. Analysis of the effect of heat treatment on the mechanical properties of forgings

In order to determine the influence of heat treatment on selected mechanical properties of forgings, microhardness and fatigue strength measurements were carried out. A special proprietary test stand was used to test fatigue strength. Figure 9a shows the draft of the workstation and Figure 9b presents the final testing stand. Tested element is fixed to the base of the station on one end, the other end is attached to a driven lever which imparts a set load on the forgings, bending them. The movement of the lever is carried out by rotating cam. Cam's height defines the maximum bend angle of the forging. The whole mechanism is powered by an electric motor with 3 kW of power and a rotational speed of 1500 min<sup>-1</sup>, through a bevel gear transmission with 24:1 ratio. Use of inverter allows for smooth change of motor's speed. In order to measure the bend angle of the tested forging, an encoder was installed on the axis of rotation of the element. Additionally, a torque sensor was placed on the main drive shaft. The measuring station is controlled via a desktop computer. In the initial testing phase, a simple application in LabView environment was created to record data from the angle and torque sensors [30].

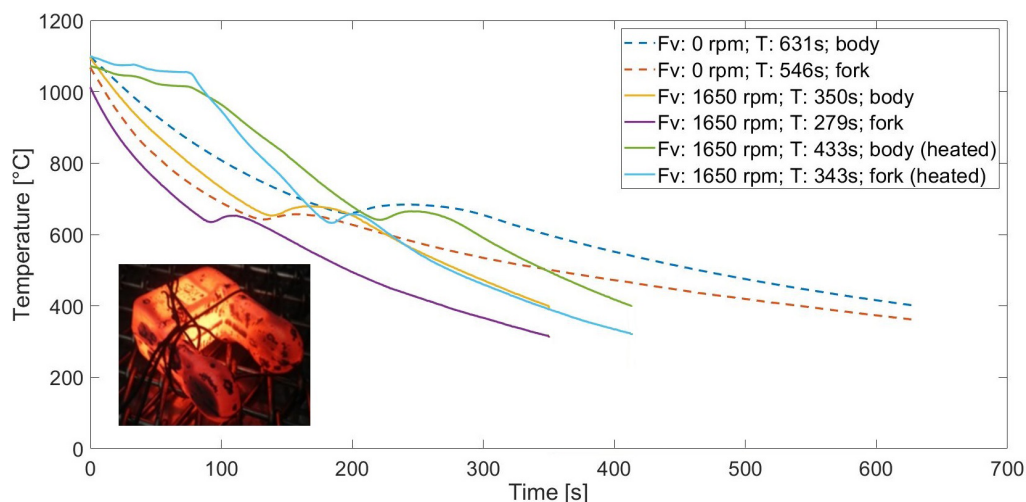


Fig. 8. Cooling course of a yoke forging within the scope of 1100°C-400°C in the function of time, for different ventilator speeds



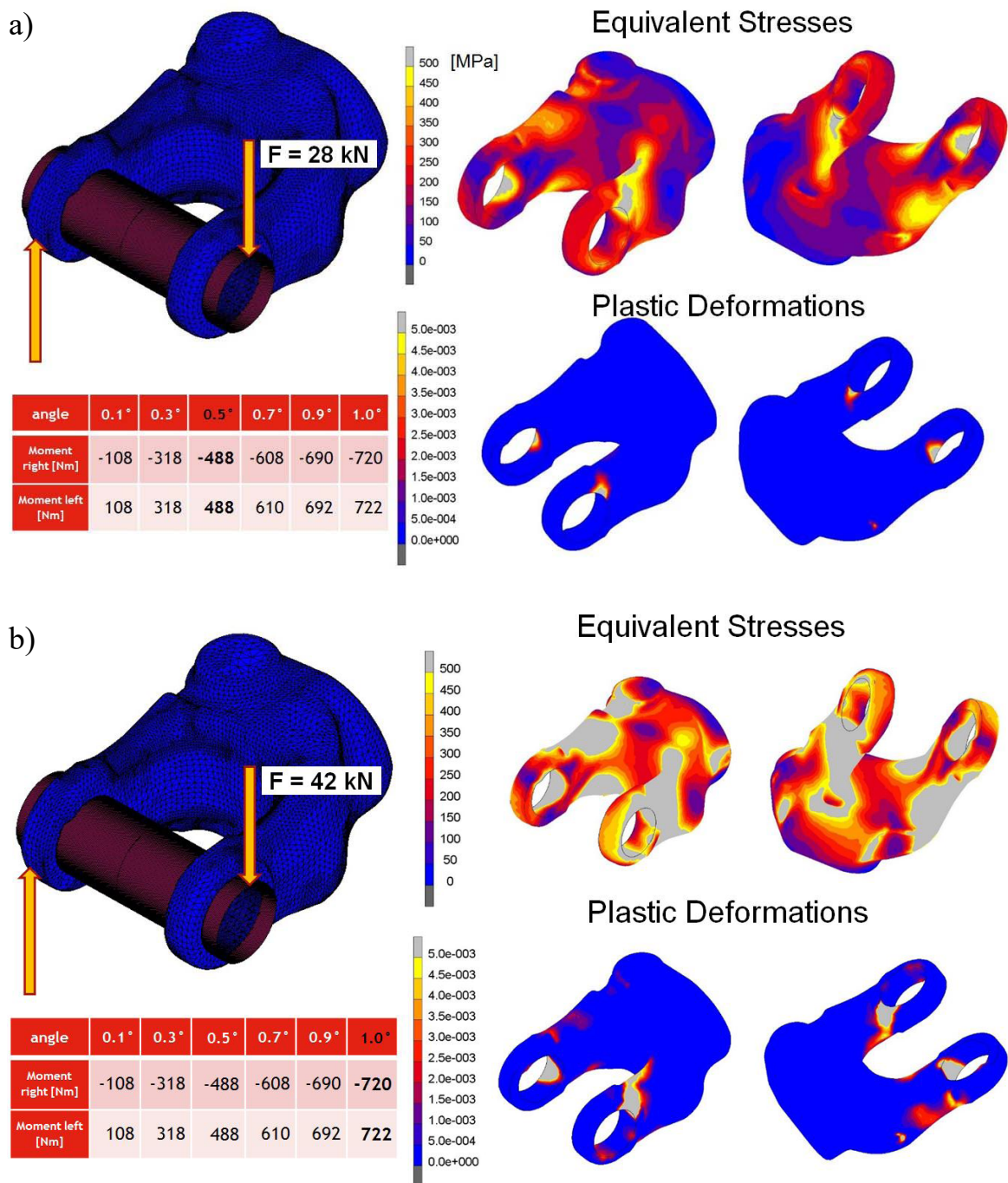
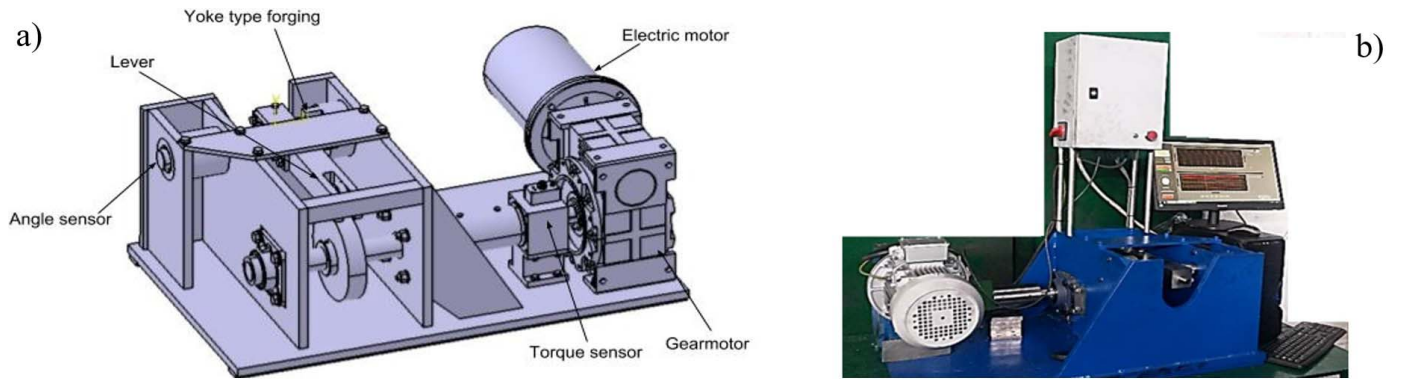


Fig. 10. Stresses and deformations at a) long-cycled tests – 0.5° b) low-cycled tests – 1°



TABLE 1

Micro hardness measurements

Single forging	Forging placed between heated forgings
231	216
232	206
237	217
Ave. 233	Ave. 213

Conducted tests and analyzes using numerical modeling allowed to determine the magnitude of the torque causing deformation of the element. In order to determine the most important parameters of the research, it was used numerical modeling, using the Marc Mentat software. Figure 10 presents the results of computer simulations for forgings concerning the determination of the torque magnitude on the occurrence of plastic deformation.

On this basis, a research methodology was proposed for the bench, a comparative method for various yoke type forgings and variants of the heat treatment. It was decided to conduct two types of durability tests: low-cycled (causing permanent deformation after a few cycles) and long-cycled (resulting in the destruction of the element after several tens of thousands of cycles). A detailed analyse was performed for long-cycled tests for cooling of a single forging and cooling of a forging placed between the others heated forgings (see Fig. 8). A photograph of the actual element is shown in fig. 11a, and a view of the sample with holes on the tines, prepared for fastening on the stand, in fig. 11b.

Before fatigue strength the microhardness measurements were conducted for two used variants for forgings according to points required by customers (Fig. 12). The obtained results were shown in table 1.

Based on the hardness measurements carried out, it can be seen that for example tests, a single forging has a higher hardness compared to cooled from other forgings by about 20 HB. Similar relationships and test results were obtained in the case of increasing the rotational speed of windmills on the cooling line.

Forgings tested in high-cycle fatigue, which underwent fatigue cracking, were subjected to a comprehensive analysis to determine the cause of the formation of cracks. When fatigue strength (to break) was determined, 451342 cycles were obtained for a single forging (the maximum torque  $M = 432$  Nm was recorded), while for a forged on line with other forgings, the fatigue strength was over 770,000 cycles (the maximum torque  $M = 419$  Nm was recorded). A detailed exemplary results of microstructure research were carried out for forging placed between heated forgings. In Fig. 13 the picture of the damaged sample with the fatigue fracture view is shown.



Fig. 11. a) final forging, b) sample prepared for the test

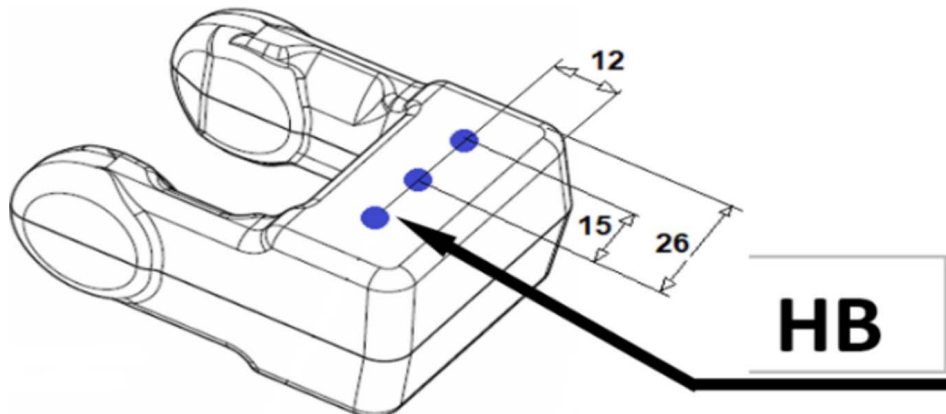


Fig. 12. The points for microhardness measurements required by customers

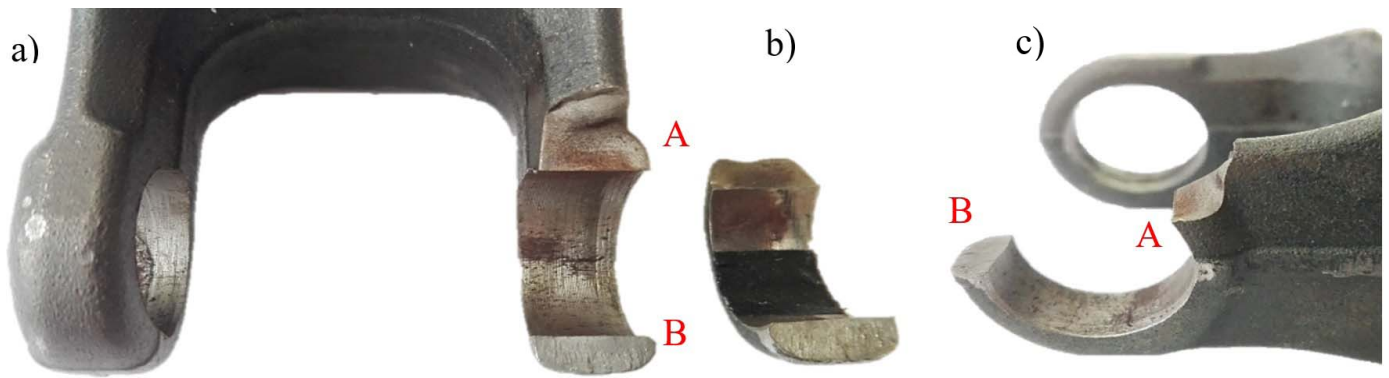


Fig. 13. View of a cracked sample at the fatigue fracture site after 773 ,000 cycles, a) plan view, b) sample selected for testing, c) side view

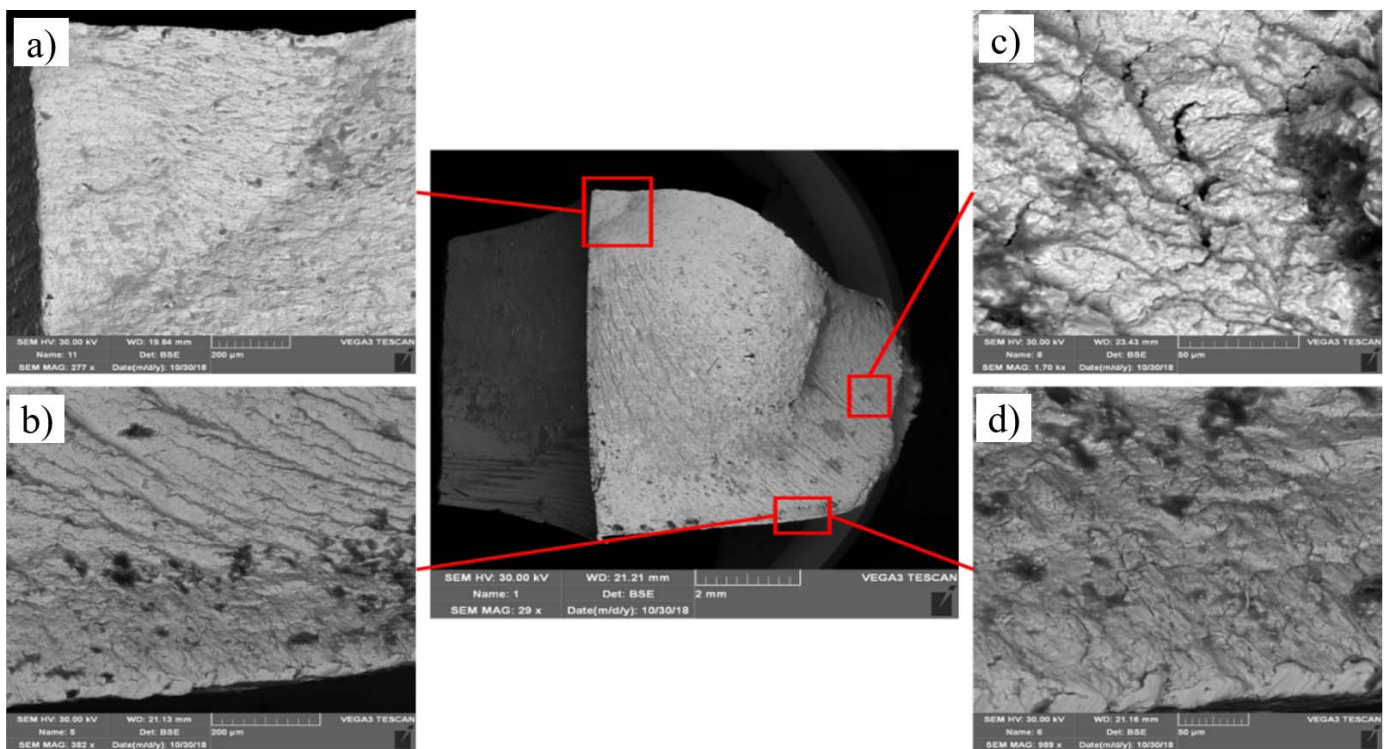


Fig. 14. The SEM view of a fatigue fracture A from the sample after a fatigue test of 773 000 cycles: a)-d) enlarged areas

The sample shown in Fig. 13 has cracked in two places, which caused a complete separation of the part of the forged ear from the rest of the detail. In Fig. 13a and 13c, both surfaces were marked with letters A and B. On the basis of observations of cracks occurring on other forgings, and on the basis of numerical simulations [19], it was determined that fatigue crack initiation occurs on surface A, where the greatest stresses occur. Selected results of the fracture A observation are shown in Fig. 14.

Observation of fracture A on the scanning microscope revealed: surface structure, the presence of numerous micro-cracks, crack propagation traces, traces of local deformations and differences in microstructure. First of all, in Fig. 14a, it is possible to recognize the crack initiation site in the upper left corner, so-called breakout point. In the same picture, the line of the clear border of the brittle fracture zone with the focal point is visible. From this line, the fatigue crack developed gradually,

which gradually weakened the cross-section and ultimately led to the rapid destruction of the element by fast brittle fracture (when the strength of the material was exceeded in the intact part of the cross-section). Most of the fracture surface is a rapidly damaged section, i.e. the residual zone (Fig. 14b and 14d), which can be equated with the coarse-grained structure, and its significant share in the total area of the fracture that indicates a high value of stress in the sample during the test. The surface observations in Fig. 14c and 14d confirm the effect of the applied heat treatment on the fatigue strength of the forgings, because in the surface area another fracture structure is visible, at a depth of up to 0.2 mm, which is smoother and flatter. This indicates a greater tendency to cracking and propagation of material cracks in the forging surface layer, which may be due to the type of heat treatment being carried out and the decarburization occurring during this treatment.

## 5. Directions of further research

In the future, there are plans to expand the elaborated semi-industrial test stand, especially the controlled cooling line, with an additional system enabling measurements of the air flow speed, with the measurement scope of 0-10 m/s. and applied sensor can enable an axial measurement. The use of these devices will make it possible to determine the temperature distribution as well as the air flow inside the chamber. The further part of the research also includes a series of tests realized on forgings of a different type with different geometries, sizes and made of different materials. What is more, the authors are planning to expand the test stand with regulated throttles, which will make it possible to set any air flow direction inside the cooling chamber, which, unfortunately, may, in turn, have an effect on the interactions. That is why numerical modelling CFD (e.g. by means of the Abaqus program) will be applied. Owing to a more thorough examination of the air flow in the chamber, both mathematically and experimentally, it will be possible to design a cooling chamber in such a way so that the generated air rotation is used in the most effective way. Also, an expansion of the test stand with a system enabling a non-contact temperature measurement on the surface of the examined elements by means of a pyrometer or a thermovision camera is scheduled. The use of these devices will make it possible to determine the distribution of the cooling rates in the particular sections of the cooling chamber.

The future research will also include a cycle of thermal treatments performed on forgings and a comparison of their mechanical properties with the properties of forgings subjected to the traditional thermal treatment. It is also planned to simultaneously use the developed stand for testing fatigue strength in order to determine the operational properties of forgings, from which key elements for the automotive industry are made, because such information is an added value that is also important for the end customer.

## 6. Summary and conclusions

The presented investigations performed on the designed test stand, especially on the prototype controlled cooling line, point to the possibility of implementing thermal treatment with the use of the heat generated during the forging process. It is an obvious fact that owing to the application of such a treatment, a significant amount of energy is gained, as there is no need to cool and then (at least twice) re-heat the material, which significantly lowers the production costs and reduces the time of the treatment. The presented preliminary research results show that through a proper selection of the time-temperature parameters as well as by way of further investigations, it is possible to select these parameters in such a way that, depending on the size of the forging and the assumed efficiency of the industrial process as well as the quality of the product, we can design a thermal treatment process with the use of the forging heat,

in order to obtain such properties which are even better than the ones assumed, as compared to the traditional, expensive and time-consuming thermal treatment performed after the forging. Through the optimization of the controlled cooling line, it is possible to reduce even further the production costs of forged products with specified operational properties.

In addition, the combination of the developed line with the fatigue strength test stand will allow to determine the impact of heat treatment applied on the mechanical and operational properties of forgings, which will further confirm the results of the tests.

## Acknowledgements

This study was founded by National Centre for Research and Development, Poland (grant no. TECHMATSTRATEG1/348491/10/NCBR/2017).

## REFERENCES

- [1] Z. Gronostajski, Z. Pater, L. Madej, A. Gontarz et al., *Archiv. Civ. Mech. Eng.* 3, 898-941 (2019), DOI: 10.1016/j.acme.2019.04.005
- [2] M. Hawryluk, A. Dolny, S. Mroziński, *Archiv. Civ. Mech. Eng.* **18**, 465-478 (2018), DOI: 10.1016/j.acme.2017.08.002.
- [3] S. Maropoulos et al., *Engineering Fracture Mechanics* **71**, 1695-1704 (2014).
- [4] P. Skubisz, *Stal, Met Nowe Technol.* **9-10**, 66-70 (2015).
- [5] A. Milenin, T. Rec, W. Walczyk, M. Pietrzyk, *Steel. Res. Int.* **87**, 519-528 (2014), DOI: 10.1002/srin.201500124
- [6] S. Samanta, P. Biswas, S. Giri et al., *Acta Mater.* **105**, 390-403 (2016), DOI: 10.1016/j.actamat.2015.12.027
- [7] D. Kim, S.-J. Lee, B.C. De Cooman, *Metall. Mater. Trans. A* **43**, 4967-4983 (2012), DOI: 10.1007/s11661-012-1338-7.
- [8] S. Ebner, C. Suppan, R. Schnitzer, C. Hofer, *Mater. Sci. Eng. A* **735**, 1-9 (2018), DOI: 10.1016/j.msea.2018.08.026
- [9] K. Radwanski, R. Kuziak, R. Rozmus, *Archiv. Civ. Mech. Eng.* **19**, 453-468 (2019), DOI: 10.1016/j.acme.2018.12.006
- [10] J. Sińczak, ARBOR FP Kraków (2013).
- [11] T. Li, G. Liu, M. Xu et al., *Acta Metall. Sin.* **53**, 1055-1064 (2017), DOI: 10.11900/0412.1961.2016.00457
- [12] S. Li, H. Ji, B. Wang, Y. Mu, *Archiv. Civ. Mech. Eng.* **19**, 391-404 (2019), DOI: 10.1016/j.acme.2018.11.006
- [13] ASM Handbook Committee, *ASM Handbook. Volume 4: Heat treatment* (1991).
- [14] M.M. Avedesian, H. Baker, *ASM specialty handbook: magnesium and magnesium alloys. ASM Int Mater Park OH 15* (1999).
- [15] K.P. Rao, Y.V.R.K. Prasad, K. Suresh, *Mater. Sci. Eng. A* **558**, 30-38 (2012), DOI: 10.1016/j.msea.2012.07.040
- [16] C. Pandey, M. M. Mahapatra, P. Kumar, F. Daniel, B. Adhithan, *Archiv. Civ. Mech. Eng.* **19**, 297-310 (2019), DOI: 10.1016/j.acme.2018.10.005,
- [17] D.D. Krueger, *Miner., Metals & Mater. Soc.* 279-296 (2012). DOI: 10.7449/1989/superalloys\_1989\_279\_296
- [18] E.E. Brown, *American Institute of Mechanical Engineers* (1972).



- [19] M. Opiela. *J. Mater. Eng. Perform.* **23**, 3379-3388 (2014), DOI: 10.1007/s11665-014-1111-8
- [20] J. Adamczyk, A. Grajcar, 11th International Scientific Conference Achievements in Mechanical & Materials Engineering, 1-6 (2002).
- [21] M.S. Anwar, S. Prifiharni, E. Mabruhi, *IOP Conf. Ser. Mater. Sci. Eng.* **202**, 12-37 (2012), DOI: 10.1088/1757-899X/202/1/012037.
- [22] B. Garbarz, M. Adamczyk, *Stal, Met. Nowe Technol.* **7-8**, 11-15 (2018).
- [23] V.K. Chandravanshi, A. Bhattacharjee, S.V. Kamat, T.K. Nandy, *J. Alloys Compd.* **589**, 336-345 (2014), DOI: 10.1016/j.jallcom.2013.11.014.
- [24] Y. Deng, Y. Zhang, L. Wan, X. Zhang, *Mater. Sci. Eng. A* **554**, 33-40 (2012), DOI: 10.1016/j.msea.2012.05.102.
- [25] P. Skubisz, H. Adrian, *Numer Heat Transf. Part A Appl.* **73**, 163-176 (2018), DOI: 10.1080/10407782.2017.1421362.
- [26] B. Garbarz, T. Bołd, *Met. Sci.* **18**, 357-361 (1984). DOI: 10.1179/030634584790419926.
- [27] P. Skubisz, A. Łukaszek-Solek, *Arch. Metall. Mater.* **62**, 2247-2254 (2017), DOI: 10.1515/amm-2017-0331.
- [28] Y. Tomita, T. Okawa, *Mater. Sci. Technol.* **11**, 245-251 (1995). DOI: 10.1179/mst.1995.11.3.245.
- [29] P. Skubisz, J. Sinczak, *Aircr. Eng. Aerosp. Technol.* **90** (5), 713-719 (2018), DOI: 10.1108/AEAT-12-2015-0253.
- [30] P. Jabłoński, M. Hawryluk, J. Ziemia, M. Rychlik, 27th International Conference on Metallurgy and Materials, 384-390 (2018).