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precipitation hardening,
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forgings heat treatment

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ASYMMETRIC COOLING PROCESS FOR TOWING HOOKS FORGINGS

The essence of the new solution is the implementation of asymmetric cooling technology for forgings made of 38MnVS6 and 30MnVS6 steel in order to homogenize the mechanical properties through precipitation hardening. The developed process for forgings with significant cross-sectional asymmetry was practically implemented in the conditions of the Kuznia Matrycowa in Lublin. The heat treatment conveyor using the given solutions is 10 m long, and the time needed to complete the controlled cooling of forgings, divided into two zones, is 7–10 minutes. Cooling curves are controlled by a fan system with individual measurements and air flows in each section. The obtained results indicate the validity of using this solution, especially in terms of reducing the grain size and increasing the mechanical parameters of the products, including the impact strength parameter, which is crucial when accepting towing hooks manufacturing.

1. INTRODUCTION

Currently, the most frequently used types of heat treatment, carried out on a large scale in the production of steel forgings, are normalization, hardening and isothermal annealing, which are usually performed separately from the forging process [1–5]. A typical cycle of conventional heat treatment of die forgings includes: heating the charge to the initial forging temperature, i.e. approximately 1100–1300°C, multi-stage forging on a forging unit (press, hammer, etc.); forgings after the forging process have a temperature of about 1100°C and, depending on the technology, can be hot processed; they are then cooled in an furnace chamber or sometimes on a temperature-controlled conveyor. After that they are heated again to normalize and cooled in air or heated to the austenitizing temperature and cooled in oil, water or other medium. The latter procedures include tempering in the case of hardening, i.e. heating the forgings to the temperature of 550–650°C and cooling them to ambient

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temperature, straightening (calibration) of the forgings after hardening and finishing annealing [6–9].

The key research problem is to obtain a homogeneous steel structure after the precipitation hardening process in geometrically complex forgings with different heat capacity in individual areas. The precipitation hardening process involves cooling the forgings from the forging temperature in order to obtain steel with a specific microstructure [10—12]. This action is related to obtaining the required mechanical parameters (hardness, impact strength and tensile strength). This process is successfully used for forgings with the same heat capacity in whole specified areas. In the case of forgings with complex geometry, the above process is unstable and is characterized by heterogeneity of the steel microstructure for individual areas of the forging due to different cooling rates in different cross-sections. The precipitation hardening process is carried out using conveyors enabling controlled cooling of the workpiece. The technological problem is the lack of devices enabling the process to be carried out with the current state of precipitation hardening technology for forgings with complex geometry while maintaining a uniform steel structure. The key problem is the uneven cooling process in cooling conveyors, causing a non-uniform microstructure of the steel, which translates into non-uniform mechanical parameters of the product. The scope of the research included: solving the identified research problem by developing an innovative conveyor with a movable partition, thermal insulation enabling asymmetric cooling parameters. The homogeneous structure of the steel after the process will be achieved by conducting experimental tests enabling the creation of a matrix of asymmetric cooling parameters (conveyor operation) adapted to different cross-sections of the cooled details (heat capacity) and different types of steel. Each developed matrix will allow for obtaining a model (or close to the model) cooling curve ensuring maximization of the mechanical parameters of the product by obtaining demanded microstructure.

2. RESEARCH PROBLEM–CURRENT STATE OF TECHNOLOGY

Mechanical properties such as hardness, impact strength and durability are developed through a controlled cooling process, during which changes occur in the material's microstructure. The key element in achieving appropriate parameters is to ensure high precision of the cooling process, which should optimally guarantee an ideal, laboratory-obtained cooling curve reflecting the changes occurring in the steel. With the current state of technology, process control is extremely complicated. The cooling process usually consists of three stages of material transformation, carried out using special cooling conveyors divided into modules, equipped with a number of cooling conveyor devices enabling control of changes in the temperature of the forging, such as fans and sprinklers. The key problem today are forgings with complex geometric shapes. Products of this type are characterized by different heat capacity in different parts, resulting from their different shape. An example would be a towing hooks, which has a small diameter in one part and ends with a thick adapter. The part of the product that contains less material has a lower heat capacity and therefore cools down faster. Currently used conveyors are usually divided into three modules, each of which is responsible for a different stage of changes in the steel. It is possible to ensure uniform cooling parameters within one module, but this is not possible for the entire volume of the forging - the cooling process in such conditions is uneven. The second problem is the construction of conveyors and the design of refrigeration equipment. Our own research shows that they do not allow obtaining a theoretical cooling curve which, in an ideal environment, covers every phase of the transformation, including subphases in which the temperature should be maintained or cooling should be accelerated/slowed down.

The most important challenges faced by the proposed method include:

- Development of the structure of a modular conveyor for controlled cooling, which will use its own partition, adjustable in the vector and rotational axes, enabling the implementation of asymmetric cooling conditions in the area of each module,
- Development of the design of individual modules, ensuring the ability to accurately reflect the laboratory cooling curve, in particular in the area of the stage of austenite grain refinement (module 1) and the stage of transformation of austenite into pearlite and ferrite (module 2),
- Development of the design of cooling modules enabling control of the width of the supplied cooling air stream,
- Development of an asymmetric cooling process for forgings in industrial conditions of steel grades used in the automotive industry using the developed conveyor.

3. TOWING HOOK–PRECIPITATION HARDENING

The use of controlled cooling in alloy steels is aimed at eliminating grain growth and obtaining a ferritic-pearlitic structure, which is related to the cooling rate. At a temperature in the range of 850°C÷800°C, austenite transforms into ferrite. From a temperature of 850°C, transformations occur that affect the microstructure of steel.

Due to the diverse range of products currently manufactured by Kuznia Matrycowa, a representative, detailed analysis was carried out on the forging with the largest difference in cross-sections and clear asymmetry, i.e. a towing hook with an adapter belonging to the entire series of products with a similar shape and size – Fig. 1.

The sketch in Fig. 2 of the towing hook forging in question shows the locations of the tested temperatures during cooling. A thermal imaging camera was used to carry out the analysis. The piece was induction heated in a NIP 800 furnace to a temperature of 1250°C. In the next step, a 3T die hammer was used to make a forging. The temperature of the dies was in the range of 120°C–160°C, and the temperature of the forgings was 1180°C–1210°C. Subsequently, the forging was trimmed using a press 2500 kN, and then hot straightened and punched using a press with a pressure of 4000 kN.

The first experimental tests for the forgings in question after trimming were carried out using an existing, old belt conveyor with an insulating casing. The initial temperature in the forging from the 4000 kN press was in the range of 1060°C – 970°C. The time to pass through the conveyor is 510 s. The entry temperature of the forging onto the conveyor at the marked points was from 950°C to 1050°C. The chart (Fig. 3) shows the results in three sections according to Fig. 2.

Fig. 1. Forging of the towing hook with an adapter

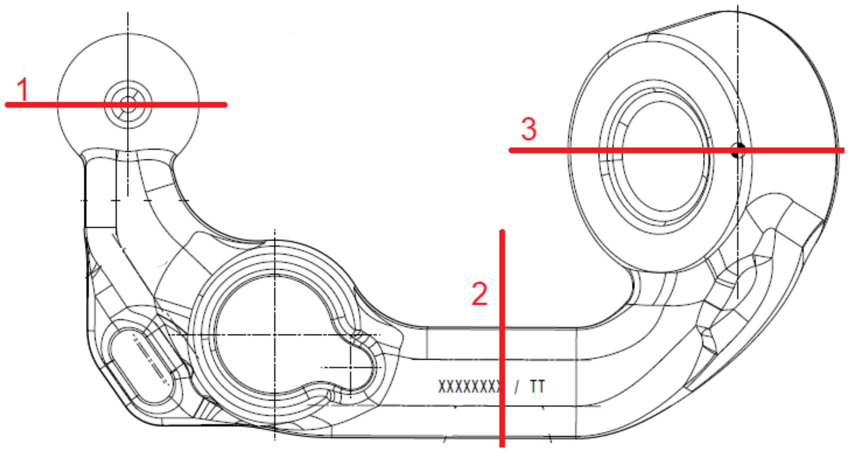


Fig. 2. Sketch drawing of a towing hook made of 30MnVS6 steel

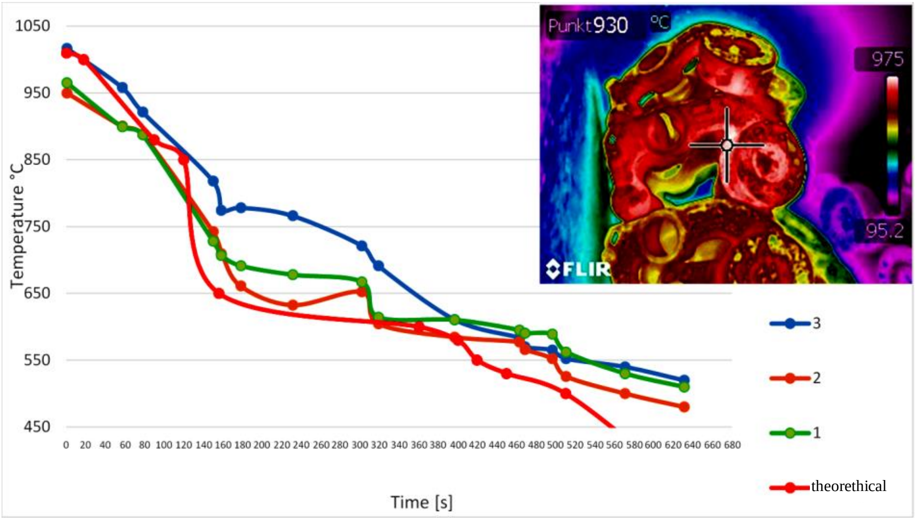


Fig. 3. Temperature distribution over time – Towing hook 100XXXXX. Cooling curve on the current conveyor with a theoretical cooling curve plotted

Based on data obtained with a thermal imaging camera, it was found that in smaller cross-sections of the forging, the temperature in the initial phase drops faster. After 150 seconds, the temperature distribution ranges from 820°C to 729°C. The initial cooling curves determined were within the temperature gradient range of 1°C–1.5°C/s. The obtained cooling curves show relatively large temperature differences in the cross-sections. This results from the cross-section of a geometrically complex forging. The area of cross-section 3 (according to Fig. 2) is relatively larger than cross-section no. 2 and 1, in which the material cools much faster. Taking into account the shape of the forging, it can be assumed that it geometrically consists of two parts, differing significantly in thermal capacity. The forging element, called the "adapter", is characterized by a large cross-section and mass, and as a result, a large heat node that accumulates energy and requires high-intensity cooling methods. Additionally, the "adapter", as can be seen in the strain intensity distribution (Fig. 4), is characterized by the lowest throughput in the entire forging. It should therefore be assumed that the grain, due to the low intensity of deformation, will have very favourable conditions for excessive growth. The temperature changes given in Fig. 3 concern the surface of the forging and the theoretical assumptions provided by the recipient of the products. These results were verified using the Simheat software from Transvalor. Figure 4 graphically shows the distribution of strain intensity in a towing hook forging.

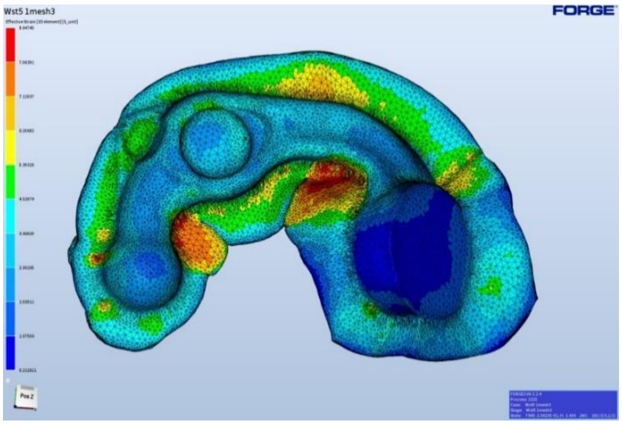


Fig. 4. Distribution of the effective strain for a towing hook type forging

The second geometric area of the towing hook forging includes the ball and the arm. This part of the forging is characterized by small cross-sections that do not constitute too large thermal nodes with a tendency to quickly sub cool, which requires less intensive cooling methods. It should therefore be assumed that due to the high intensity of plastic deformations, the grain should be finer.

In order to limit the heterogeneity of the structure resulting from different cooling conditions of two parts of the forging, which are so different in terms of thermal conditions, a second general assumption can be defined regarding the construction of the conveyor, namely that each of the cooling modules of the device should be equipped with an isothermal shutter adjusted in two axes, constituting a thermal barrier, creating two heat chambers with the possibility of obtaining different cooling parameters for geometrically and thermally different parts of the forging.

The actual B-Y treatment process consists of several phases in which different cooling rates are expected. The first phase runs between the temperature of the end of forging and the beginning of the ferritic transformation, the second phase is the ferritic transformation, the third phase is the pearlitic transformation, and the fourth phase is the maximum bypassing of the bainitic transformation and the elimination of the Widmannstätten structure. Therefore, a device for controlled cooling from the forging temperature should consist of four independent cooling modules that can be used to implement different cooling conditions. Additionally, the B-Y cooling conveyor is intended to carry out the so-called "asymmetric cooling process from the forging temperature" of two parts of an axially asymmetric forging, with two significantly different heat capacities. For this purpose, each of the four modules should be equipped with a thermal insulation partition, the task of which will be to divide each module into two parts, which will enable the creation of asymmetric cooling conditions.

Based on the data collected in this way and the assumptions made, the process of determining the dimensions and technological and operational assumptions of the designed controlled cooling conveyor began. These assumptions concerned the dimensions of products with a planned length of up to 450 mm, an assumed weight of forgings of approximately 7–8 kg/piece, a conveyor length of up to 10 meters and a process execution time of approximately 600 seconds.

Based on the findings regarding the length of forgings intended for heat treatment, the working width of the conveyor was assumed to be 450 mm. Taking into account its length of 10,000 mm and height of 350 mm, this assumption allowed for the verification of the heat flow, taking into account heat flows with values in the range of 3–12kW/m2K for air and 6 kW/m2K for the water mist. A 3D model of the designed conveyor according to the given concept is shown in Fig. 5, and the finished conveyor is shown in Fig. 6. The operation of the conveyor according to the ACPF concept is controlled by executive systems and a controller, the screen of which is shown in Fig. 7, and the temperature measurement results for subsequent conveyor zones respectively ball and adapter are given in Table 1.

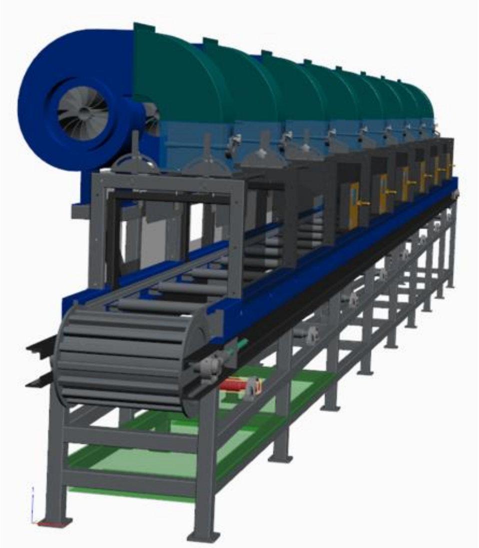


Fig. 5. The original concept of a conveyor for controlled cooling of forgings according to ACPF technology - general view

Fig. 6. Conveyor and products leaving controlled cooling

Sterowanie ręczne

	Sekcja 1	Sekcja 2	Sekcja 3	Sekcja 4	Sekcja 5	Sekcja 6	Sekcja 7	Sekcja 8
Temperatura 1 [oC]	179	279	207	202	210	179	206	217
Temperatura 2 [oC]	180	307	216	230	236	236	575	180
Prędkość Aktualna [obr/min]	500	300	300	300	300	400	400	400
Prędkość Zadana [obr/min]	500	300	300	300	300	400	400	400

Licznik sztuk 9669

0.90 m/min

0.90 m/min

Fig. 7. Conveyor operation controller screen

Table 1. Current temperature readings

Test zone	Temperature at the hook ball	Temperature at the hook adapter
Temperature inlet	1037.5	1050
1	875.4	924.7
2	797.5	832.6
3	746.6	788.7
4	689.8	736.4
5	641.2	689.0
6	652.8	661.7
7	649.9	629.2
8	605.0	635.9
Temperature outlet	547.1	653.2

For such tests, the results were determined in terms of the obtained microstructures and mechanical properties, and all assumptions regarding the detailed requirements of one of the recipients of the forgings were met. The results obtained regarding selected cooling curves are summarized in Table 2.

Table 2. Summary of temperature measurement results over time for towing hook 100XXXXX made of 30MnVS6 material (A- adapter, K- ball, MES – numerical calculations, EXP – experimental results)

Time, s	A-MES	K-MES	K-EXP3	A-EXP3	K-EXP2	A-EXP2	K-EXP1	A-EXP1
0	956	932	875.4	924.7	821.3	861.0	792.9	840.5
60	882	873	797.5	832.6	714.6	796.4	676.3	741.1
120	826	814	746.6	788.7	654.5	690.7	660.9	681.3
180	798	781	689.8	736.4	659.5	659.4	610.4	631.4
240	773	757	641.2	689.0	605.0	659.3	599.1	652.5
300	750	738	652.8	661.7	561.2	637.6	538.1	600.7
360	733	720	649.9	629.2	505.2	592.5	501.7	543.4
420	714	696	605.0	635.9	475.4	550.5	465.2	542.2
480	689	668	547.1	653.2				
540	656	631						

For the data collected in this way, a summary chart was prepared illustrating temperature changes in both zones of the forging over time–Fig. 8. Differences in results, reaching an average of approximately 100°C, are due to the fact that the pyrometer measurement took place only on the surface of the forging, where the measuring is lowered by intensive air cooling.

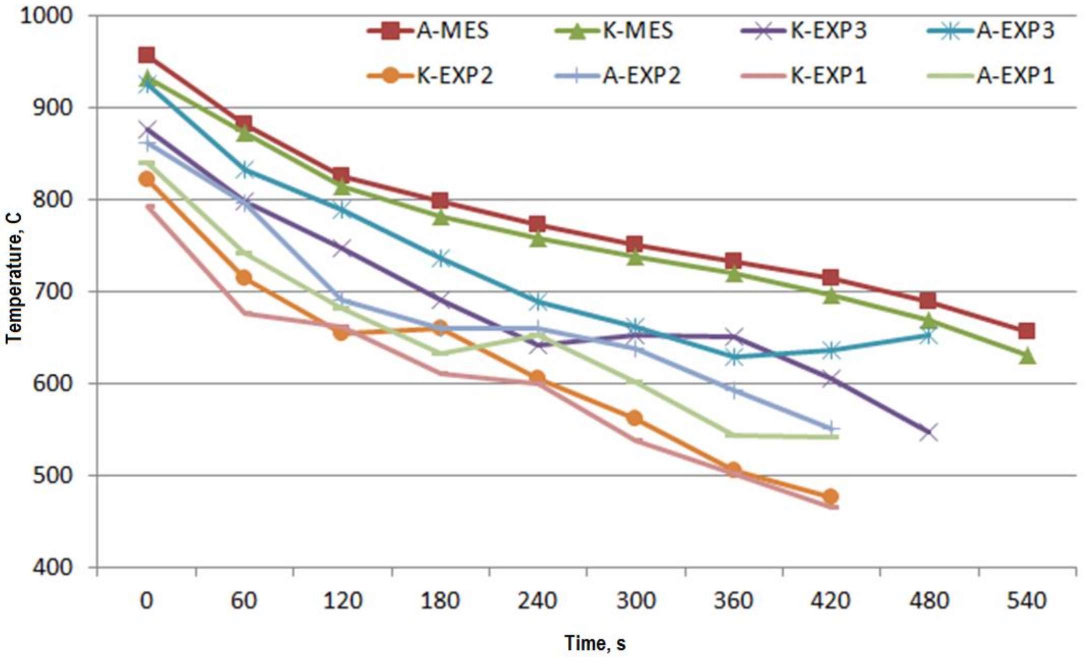
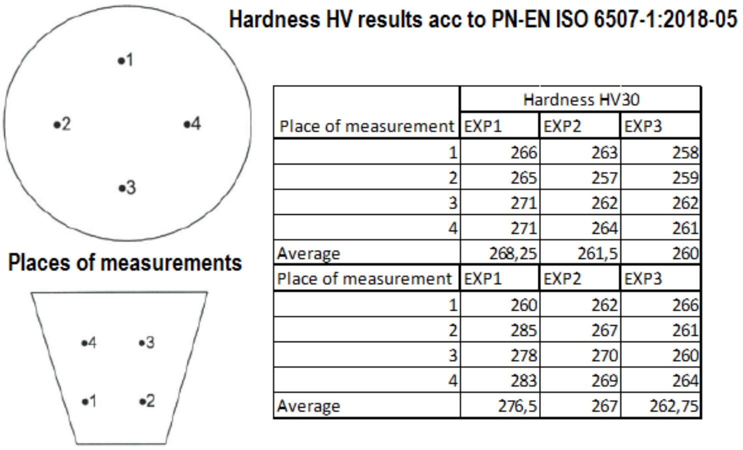


Fig. 8. Summary of the results of changes in process parameters for the towing hook forging 100XXXXX made of 30MnVS6 material (A - adapter, K - ball, MES - numerical calculations, EXP - experimental results)

Subsequent changes introduced in the conveyor operation (EXP 1, EXP 2 and EXP 3) indicate a decrease in cooling efficiency over time, until the temperature values in the adapter zone at the end of the process they will begin to increase slightly. This is due to the accumulation of heat inside a relatively large volume of material concentrated in this zone, reducing the efficiency of the fan system from 100% (EXP1) to 80% (EXP2) and 55% (EXP3). The effect of the conducted tests is to limit the variation in hardness in the tested cross-sections of forged products, which is summarized in Fig. 9.



Hardness HV results acc to PN-EN ISO 6507-1:2018-05

	Hardness HV30		
Place of measurement	EXP1	EXP2	EXP3
1	266	263	258
2	265	257	259
3	271	262	262
4	271	264	261
Average	268,25	261,5	260
Place of measurement	EXP1	EXP2	EXP3
1	260	262	266
2	285	267	261
3	278	270	260
4	283	269	264
Average	276,5	267	262,75

Fig. 9. Distribution of hardness HV according to measurement places in presented areas

The research also compared the structures obtained in the forging in the adapter zone and the ball, where more coarse-grained structures were noted in the adapter zones. This is directly related to the storage of heat and the lower plastic processing of this zone, where, when shaping the forging, it remains the same diameter of the charge bar during rolling. The results obtained for the adapter zone and the ball zone of the hook forging are shown in Fig. 10.

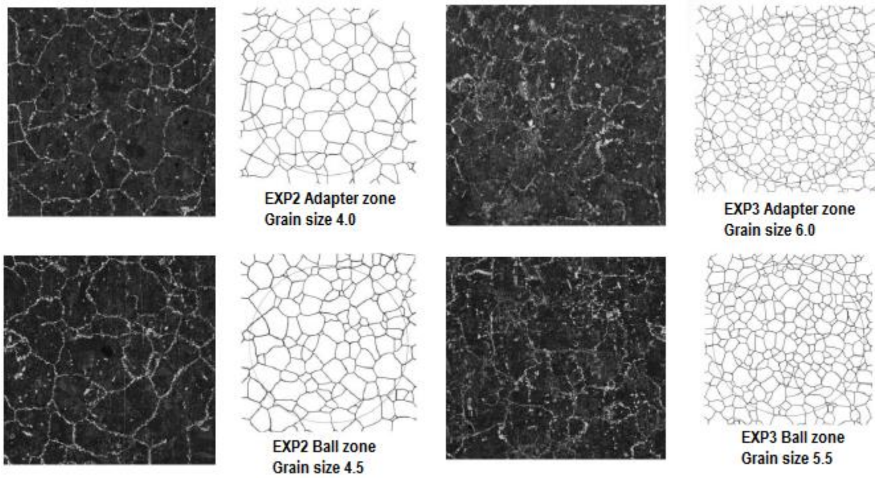


Fig. 10. Differences in grain size after the introduction of controlled and separated cooling of both zones of the forging

The introduction of controlled and separated cooling of both zones of the forging contributed to obtaining similar grain sizes throughout the forging, which was one of the goals of introducing the new cooling line. The obtained differences do not successively exceed the value of 0.5, which was not possible to obtain without varying the cooling efficiency of this type of products.

The consequence of increasing the homogeneity of the structure is also a smaller spread of impact strength measurement results. The work carried out in this area is intended to make it easier to meet the requirements of customers who are gradually narrowing their requirements regarding the properties of forgings (hardness, impact strength) and who are increasingly introducing new structural requirements that were not previously required.

4. CONCLUSIONS

The experimental research results regarding the obtained mechanical properties obtained in the course of the work indicate the possibility of further improvement of the process by more precise adjustment of the conveyor controller settings due to the increased repeatability of the parameters intended for heat treatment. Current implementation works related to the launch of a robotic forging line on a 40MN press coupled with a cross-wedge rolling mill and a device for bending semi-finished products are going in this direction.

Another conclusion drawn directly from the research is the need to take into account the correction of temperature readings for cooling the surface zones of the forging, where these differences may reach approximately 80–100°C. The current temperature change charts already take this effect into account, but it was not taken into account at the beginning of the tests. Experimental conclusions indicate the need to introduce an additional correction factor due to the compact shape of heat-treated products. These tests will be successively supplemented as the products manufactured and heat treated in the conveyor change.

Analyzed in terms of cyclograms of process flows and the use of robots (7 pieces), production cycles may differ by up to approximately 2 seconds, depending on the accuracy of intra-operative transfer of semi-finished products between nests. The planned launch of a forging line, combined with the use of a heat treatment conveyor in the form of precipitation hardening, will significantly increase the repeatability of these parameters, especially in the case of asymmetric products. Meeting the above assumptions determines the full functional implementation of the new solution. The grain size distributions obtained in experimental tests (Fig. 10) indicate the possibility of obtaining products with a grain size of no more than 5 on the ASTM112 scale. The presented results and the applied method of controlled cooling in asymmetric conditions have already been reflected in the draft standard for the acceptance of towing hooks forgings. This document is intended by the recipient to enter into force in 2025.

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Title: Development of an innovative ACPF (Asymmetric Cooling Process for Forgings) technology intended to implement the hot precipitation hardening process, which guarantees the achievement of the lowest spread of mechanical parameters of the finished product on the market. Work realized in years 2019-2023 in Kuznia Matrycowa in Lublin thanks to founds from POIR.01.01.01-00-1966/20.

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