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STUDY OF THE FORGING PROCESS OF HIGHLY ALLOYED STEEL FORGINGS ON HYDRAULIC PRESSES

Purpose. *To conduct a chronometric study of the forging process of high-alloy steel grades on hydraulic presses to identify ways of applying resource-saving technologies, which will ultimately reduce the cost of manufacturing products and increase the competitiveness of domestic manufacturers of forged products.*

Research methods. *To achieve the set goal and objectives of the study, a set of complementary scientific methods was used to obtain empirical data and analyse it. In particular, the main empirical method used in the study was chronometry, namely, the accurate measurement and recording of the duration of individual technological operations in the free forging process. To form a complete picture of the technological process and compare actual data with planned data, an analysis of technological documentation was used.*

Data processing and analysis methods made it possible to calculate the time norm fulfilment coefficient. This set of methods made it possible not only to quantitatively assess the time spent, but also to qualitatively analyse the organisation and technology of the forging process in order to develop recommendations for its optimisation.

Results. *The timing of all components of the forging technological process and subsequent analysis revealed the trends in improving the forging process of high-alloy steel grades.*

Scientific novelty. *The step-by-step timing of the forging process was accompanied by an analysis of the characteristics of the technological process, the equipment used, the mass of the ingot and the mass of the finished forging, and the working records made by the technological personnel in the forging cards after the process was completed.*

Practical value. *The results of the chronometric study of the existing technological process of forging large ingots on hydraulic presses make it possible to identify and apply technical solutions to reduce resource costs.*

Keywords: *stress-strain state of metal, highly alloyed steel, forging, hydraulic press, operation timing, resource-saving technologies.*

Introduction

Forging is the basis for the automotive, aviation and aerospace industries, shipbuilding, mechanical engineering, electrical engineering and energy.

The development of resource-saving technologies for forging expensive high-alloy steel grades can only be implemented if as many factors as possible that affect the quality of the finished product are taken into account. These factors include shape, kinematic, temperature and structural factors.

Synergistic consideration of the impact of the factors discussed will ensure a high level of technological preparation of the forging process, the quality of forgings, and their competitiveness in terms of cost.

Since consumption rates at domestic metallurgical enterprises are 15–20% higher than those of foreign manufacturers, metallurgical enterprises that pay due attention to improving production will be more competitive. Bringing forging processes at domestic enterprises up to international standards is an important and pressing task today.

Therefore, the main focus of this work is to analyse possible ways of implementing the latest approaches in the organisation and execution of heavy forging of alloyed stainless steels and heat-resistant alloys.

Analysis of research and publications

The work [1] considers the main methods of improving the quality of forging highly alloyed steels and alloys on hydraulic presses. In particular, the dependence of the stress-strain state of metal on the influence of various technological factors of the forging process was shown. The main factors include the shape of the tool (flat working surface, flat and with a bevelled surface, combined anvils, symmetrical and asymmetrical, profiled anvils, cut-out, convex, radial, stepped, anvils with crossed working surfaces, etc.) and the shape of the ingot (square, round cross-section, three-beam, multi-faceted forging, slab ingot, flat ingot, shortened, non-profit and others, round cross-section billets, for example, obtained in continuous casting machines).

The next factor affecting the distribution of the stress-strain state of metal is the kinematic factor, namely the

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kinematics of the tool's impact on the blank. And, of course, the temperature factor, which has the most significant impact on the distribution of the stress-strain state of metal.

In turn, work [2] described the main stages of designing resource-saving technologies for deforming ingots on hydraulic presses and indicated the main factors affecting the plasticity of highly alloyed steels during forging. These include:

- the presence of obstacles to sliding: restriction or inhibition of intergranular or intragranular deformation;
- high alloying of the solid solution without the formation of an excess strengthening phase;
- supersaturation of the solid solution and the formation of a dispersed strengthening phase inside the grains and at their boundaries;
- formation of a network, a brittle excess component (more often eutectic) around relatively plastic grains of the main structure of the solid solution;
- presence of two or more structural components with different properties;
- weakening of intergranular bonds at hot plastic deformation temperatures.

When developing a resource-saving technological process, it is advisable to take into account another aspect related to the design and operation of hydraulic presses. The accuracy of the obtained cross-sectional dimensions of the forging is influenced both by the characteristics of the hydraulic press itself (rigidity of the structure, inertia of the hydraulic drive) and by the resistance of the blank to deformation, which, in turn, depends on the duration of the strengthening and weakening processes in the metal of the blank [3].

Purpose of the work

The aim of the work is to conduct a chronometric study of the forging process of highly alloyed steel grades on hydraulic presses in order to identify ways of applying resource-saving technologies, which will ultimately make it possible to reduce the cost of manufacturing products and increase the competitiveness of domestic manufacturers of forged products.

Material and research methods

The study of the manufacture of large forgings from highly alloyed steels by free forging was carried out at PJSC "DNIPROSPECSTAL" in the forging and pressing shop (hereinafter referred to as FPS). For forging, ingots with a square cross-section and a trapezoidal longitudinal cross-section weighing 7.15 t, 6.5 t, 4.8 t, 4.5 (4.52) t, 3.8 t (3.77 t) and 3.6 tons, obtained in electric arc furnaces of steel-making shops SPC-2, SPC-3, and cylindrical ingots weighing 0.9-6 tons, obtained in steel-making shop SPC-5, by the method of electroslag remelting (ESR) and vacuum arc remelting (VAR). The ingots are delivered to the blacksmith press shop in a hot and cold state.

PJSC "DNIPROSPECSTAL" produces metal products of 1,200 profile sizes from more than 800 steel grades. For optimal technological preparation of production, all steel grades are classified into 20 steel grade groups (hereinafter referred to as SGG).

To solve the research tasks set, the technological processes of production of cylindrical forged bars (forgings) from steel grades belonging to five SGG, which are in high demand among consumers and represent the technological capabilities of the enterprise, are considered (Table 1). Nickel-alloyed structural steels and alloyed tool steels are smelted in steelmaking shop No. 3, while stainless steels are produced in steelmaking shop No. 2. Steel is cast in moulds of various weights. Therefore, for the sake of accuracy in comparison and analysis of the forging process, one ingot is taken as the unit of measurement.

Table 1 – Steel grades considered in the technological process

SGG	Names of steel grade groups	Steel grade	Steel melting shop
22	Alloy structural steel	40Х2Н2МА	SPC-3
32	Alloy tool steel	4Х5МФ1С	SPTS-3
		Х12МФ	
		9Г2Ф	
40	Stainless steel	14Х17Н2	SPTS-2
40Н	Ni-alloyed stainless steel	12Х18Н10Т	SPTS-2
		03Х17Н12М2У	
49Н	Heat-resistant alloyed steel Ni	ХН77ТЮР ВД	SPTS-5

At SPC-2, steel is smelted in an open electric arc furnace with a capacity of 50 tonnes, followed by blowing in an argon-oxygen converter with a capacity of 60 tonnes and processing in a ladle furnace. This process allows low-carbon corrosion-resistant stainless steel to be obtained. The shop is equipped with an 8-tonne induction furnace for the production of heat-resistant steels and special alloys.

At SPC-3, high-quality steel is obtained by processing semi-finished products in a Daniel ladle furnace, followed by vacuuming the melt in a Mannesmann Demag vacuum furnace.

SPC-5 is equipped with ESR and VDP furnaces of various capacities, which allow the production of billets weighing 0.9-6.0 tonnes and sheet billets weighing 9.3-20.0 tonnes. ESR technology ensures the production of steel and special alloys used in the most critical industries: aviation, defence, as well as thermal and nuclear power.

Two hydraulic forging presses with a nominal force of 32 and 60 MN are used for direct forging.

Seven furnaces with a stationary hearth with an area of 13.5 m^2 and a maximum charge weight of 20.2 tonnes are used to heat the ingots before forging. five furnaces

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with a roll-out hearth with an area of 18.6 m^2 and a maximum load capacity of 55 tonnes; two furnaces with a roll-out hearth with an area of 13.9 m^2 and a maximum load capacity of 44 tonnes. On these furnaces, a single TPP (S) model thermocouple with a length of 1.0 m is installed vertically in the centre of the vault (arch) of each furnace to control the heating temperature of the ingots before forging.

Research results

The study of the peculiarities of the forging process of high-alloy steels, shown in Table 1, was carried out using the example of manufacturing due to specific customer orders. For this purpose, the process of several order items was timed step by step, the applied technological charts for the manufacture of forgings in the KPC from the above-mentioned steel grades were reviewed with a description of the technological process, the equipment used, the weight of the ingot and the weight of the finished forging, and the work records made by the technological personnel in the forging charts after the completed process were analysed.

The consolidated data of the analysis of the optimality of the technological process are grouped in Table 2 and discussed in more detail in the following sections for each steel grade.

Eight grades from five steel groups were considered. For timing from current production, steel 03Х17Н12М2У with a billet weight of 6.8 t and a forging size of Ø365±5 and steel 9Г2Ф with a billet weight of 3.77 t and a forging size of Ø225±5 were selected, in terms of the parameters of the forging process, which could be grouped with other steels. Thus, the production of bars from 40Х2Н2МА and 12Х18Н10Т steels in terms of the sequence of operations was considered analogous to the technological process of forging cylindrical bars from 03Х17Н12М2У steel, and the production of bars from 4Х5МФ1С, Х12МФ, 14Х17Н2 steels was considered analogous to the forging of bars from 9Г2Ф steels based on the same factors. The features of the forging process of heat-resistant Ni- based alloy ХН77ТЮР ВД were considered based on the data provided by the author[3].

The step-by-step timing of the forging process for 03Х17Н12М2У and 9Г2Ф steel forgings at the blacksmith press shop PJSC “DNIPROSPECSTAL” was accompanied by an analysis of the features of the technological process, the upplied equipment, the weight of the ingot and the weight of the finished forging, and the work records made by the technological personnel in the forging cards after the process was completed . The main results of the research are presented below.

The forging chart was reviewed and the technological process of forging a Ø225+5 mm bar (forging size) to a finished size of Ø202+3 mm of 9Г2Ф steel from a 3.77 t ingot was analysed. The ingot has a square cross-section and a trapezoidal longitudinal cross-section with the following dimensions: 590x590 mm top, 480x480 mm bottom, length to the profitable part 1680 mm.

The results of the technological process analysis are given in Table 2, and the forging diagram is shown in Figure 1.

The data on the yield of Ø225+5 mm bars suitable for forging from 4Х5МФ1С, Х12МФ, and 9Г2Ф tool alloy steels are calculated and presented in Table 2.

A significant part of this time, about 23%, was spent on transport operations, namely transporting the ingot from the heating furnace to the press and back in seven trips, turning it over to forge the second half of the ingot, and preparing the workpiece.

The actual forging accounted for 77% of the forging complex's operating time, which in turn was divided between the main forging operations, when the press was operating at maximum load (sedimentation and drawing operations), i.e. the equipment was used with maximum efficiency, and the time of auxiliary operations (smoothing, ticket cutting, corner filling), when only 3-4% of the press capacity was used.

In the last finishing pass, auxiliary operations and, accordingly, unproductive use of the press capacity accounted for about 40% of the total forging time.

The forging diagram (Fig. 1) shows the technological stages of obtaining a finished forged bar:

- heating of the ingot;
- forging the trunnion;
- depositing the ingot on the sedimentation plate;
- drawing to an intermediate size of 450 mm square with cutting of the leading edge (it is possible to transfer the cutting to the trailing cut);
- drawing to an intermediate size of 350 x mm;
- cutting the workpiece into 2 parts, identified as bar A and bar H, taking into account their location relative to the head of the ingot;
- drawing rod A and rod H separately to an intermediate size of 280 mm square;
- final removal – forging to a finished forging size of 235 mm.

The yield of usable billets from 4Х5МФ1С, Х12МФ, and 14Х17Н2 steel ingots, the forging of which was considered analogous to the forging of 9Г2Ф steel bars, and actually from 9Г2Ф steel ingots, ranges from 58 to 65 %.

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Table 2 – Technological process of forging a Ø230 mm bar (forging size) to a finished size of Ø202+3 mm of 9G2F steel from a 3.77 t ingot

No	Content of technological actions	No. of technological operation	Name of technological operation / forging start temperature Tn, forging end temperature Tk, ºC	Time of execution		
				of the main forging operation, s	auxiliary forging operation, s	transport operation, s
I	Settling, forging of the trunnion	1	Removing the ingot for forging Tn=1160ºC			60
		2	Forging of the trunnion	46		
		3	Settling on 630 mm square (compression up to 200 mm per press stroke)	543		
		4	Return to furnace for heating Tk=960ºC			60
			Total time for technological operations for the first removal 709 s (11 min 49 s)			
II	Forging from 630 mm square to 450 mm square	5	Removal of settled ingot 630 mm square for forging Tn=1160ºC			6
		6	Drawing (compression to 120 mm per press stroke)	443		
		7	Smoothing (compression up to 10 mm per press stroke)		13	
		8	Turning over for forging the second half of the ingot			8
		9	Returning a 450 mm square forging to the furnace for heating at 950ºC			60
			Total time for technological operations for the second removal 780 s (13 min)			
III	Forging of 450 mm square bar to 350 mm square bar	10	Removal of settled ingot 630 mm square for forging Tn=1160ºC			6
		11	Drawing (compression to 120 mm per press stroke)	29		
		12	Turning for forging the second half of the ingot			84
		13	Smoothing (compression to 10 mm per press stroke)		118	
		14	Cutting into two bars A and H	100		
		15	Returning bar A sq. 350 mm to the furnace for heating			60
		16	Return of rod H sq. 350 mm to the furnace for heating Tk = 950ºC			60
			Total time for technological operations for III removal 780 s (13 min)			
IV	Forging of rod A from 350 mm square to 280 mm square	17	Removal of rod A from the furnace Tn=1160ºC			6
		18	Drawing rod A	612		
		19	Smoothing bar A		262	
		20	Turning over to forge the second half of bar A			86
		21	Return of bar A sq. 280 mm to the furnace for heating Tk = 920ºC			60
			Total time for technological operations for IV removal 1080 s (18 min)			
V	Forging of bar H from 350 mm square to 280 mm square	22	Removal of bar H from the furnace Tn=1160ºC			60
		23	Drawing of bar H	618		
		24	Smoothing the rod H		269	
		25	Turn for forging the second half of the rod H			81
		26	Return of bar H sq. 280 mm to the furnace for heating Tk = 920ºC			60
			Total time for technological operations for V removal 1088 s (18 min 8 s)			
VI	Forging of bar A from 280 mm square to Ø230 mm (finished grade in forging dimensions)	27	Removal of bar A from the furnace Tn=1160ºC			6
		28	Drawing of the first half of bar A	25		
		29	Smoothing of the first half of bar A		151	
		30	Reversal for forging the second half of bar A			81
		31	Drawing of the second half of rod A	75		
		32	Smoothing of the second half of bar A Tk=920ºC		133	
			Total time for technological operations for VI removal 750 s (12 min 30 s)			
VII	Forging of bar H from 280 mm square to Ø230 mm (finished grade in forging dimensions)	33	Removal of bar A from the press area. Removal of bar H from the furnace Tn=1160ºC			6
		34	Drawing of the first half of bar H	202		
		35	Smoothing of the first half of the bar N		162	
		36	Turning over for forging the second half of the rod H			91
		37	Drawing of the second half of the rod H	77		
		38	Smoothing of the second half of the bar N		109	
		39	Removal of the barbell from the press zone H Tk=920ºC			60
			Total time for performing technological operations for VII removal 671 s (11 min 11 s)			
ANALYSIS OF TECHNOLOGICAL PROCESS PARAMETERS						
A. Total time of use of the forging complex (B + C) 5858 s (1 hour 37 min 38 s = 1.627 hours) Forged bar obtained in forging dimensions – 3130 kg. Productivity – 1.924 t/hour. Products shipped to the consumer – 2432 kg. Productivity – 1.495 t/hour.						
B. Transport operation time 1344 s (22 min 24 s) – 22.94% of A						
C. Forging time (main and auxiliary forging operations) 4514 s (1 hour 15 min 14 s) – 77.06% of A						
B.1 Time of main forging operations (operations 2, 3, 6, 11, 14, 18, 23, 28, 31, 34, 37) 3264 s (54 min 24 s) – 72.31% of B						
B.2 Time of all auxiliary forging operations (operations 7, 13, 19, 24, 29, 32, 34, 38) 1240 s (20 min 40 s) – 27.69% of B						
B.3 Time of main forging operations of the last finishing stroke (operations 28, 31, 34, 37) bar A – 750 s bar H – 671 s						
B.4 Time of auxiliary operations of the last finishing stroke (operations 29, 32, 34, 38) bar A – 284 s (37.87% of B.3) bar H – 271 s (40.39% of B.3)						

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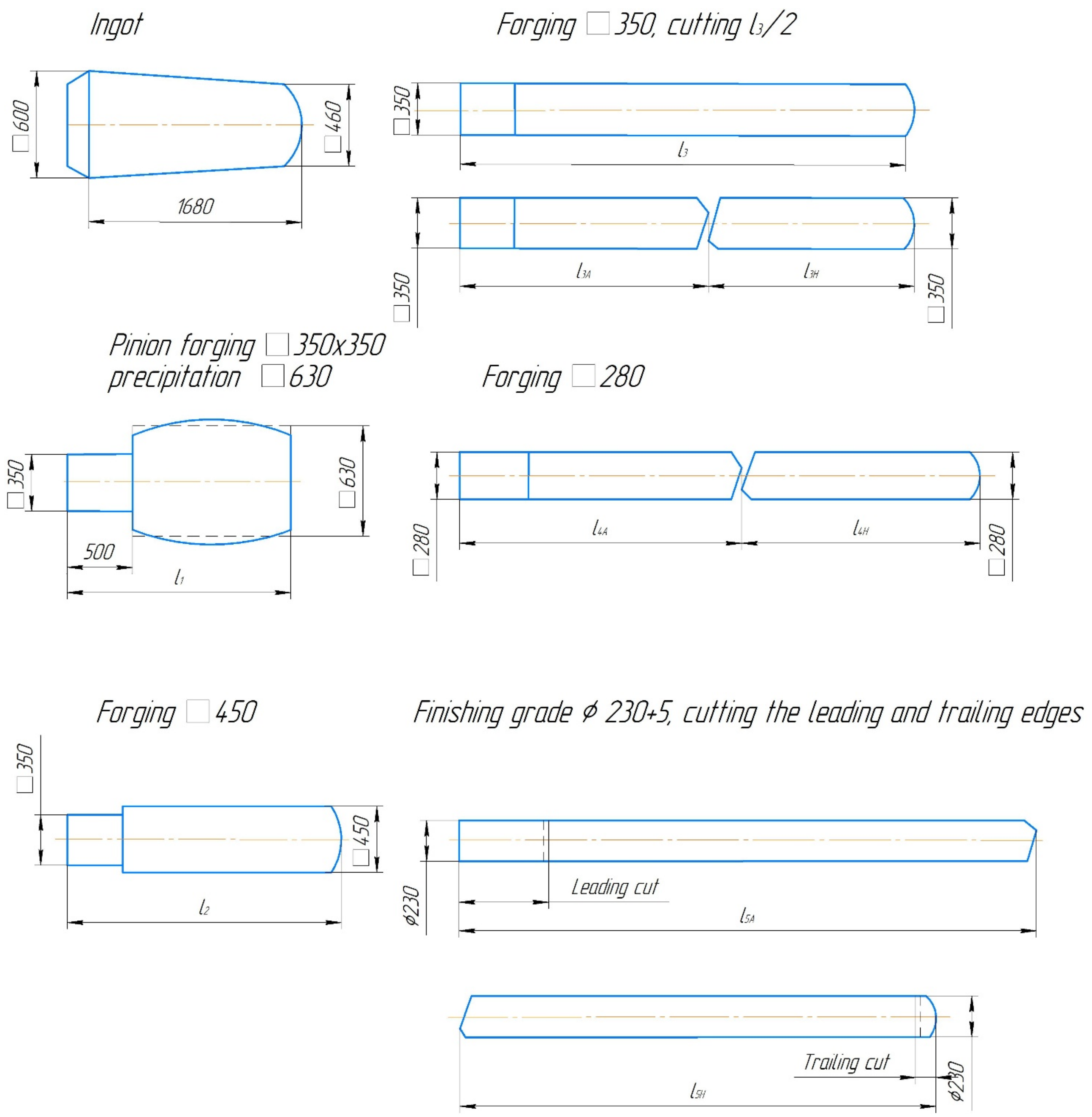

Figure 1. Diagram of forging cylindrical bars from tool alloy steel (using the example of steels 4Х5МФ1С, Х12МФ, 9Г2Ф)

Conclusions

The timing of forging large ingots of high-alloy steel grades on a hydraulic press indicates that forging accounted for 77% of the forging complex's operating time, which in turn was divided between the main forging operations, when the press was operating at maximum load (sedimentation, drawing), i.e. the equipment was used with maximum efficiency, and the time of auxiliary operations (smoothing, ticketing, corner filling), when only 3–4% of the press capacity was used. In the last finishing pass, auxiliary operations and, accordingly, unproductive use of the press capacity accounted for about 40% of the total forging time.

Thus, we can talk about the irrational use of high-cost equipment (hydraulic forging press), accompanied by increased resource costs. One way to apply resource-saving technologies could be introduction of additional equipment into the technological cycle to perform auxiliary forging operations or to replace these operations with other types of metal pressure processing while maintaining the final result of shaping.

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ДОСЛІДЖЕННЯ ПРОЦЕСУ КУВАННЯ ПОКОВОК ВИСОКОЛЕГОВАНИХ МАРОК СТАЛЕЙ НА ГІДРОПРЕСАХ

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Мета роботи. *Проведення хронометричного дослідження процесу кування високолегованих марок сталей на гідравлічних пресах для виявлення шляхів застосування ресурсозберігаючих технологій, що в кінцевому випадку дасть можливість знизити собівартість виготовлення продукції та підвищити конкурентну спроможність вітчизняних виробників кованої продукції.*

Методи дослідження. *Використано комплекс взаємодоповнюючих наукових методів, які дозволили отримати емпіричні дані та провести аналіз. Зокрема, основним емпіричним методом, застосованим у дослідженні, був хронометраж, а саме: точне вимірювання та фіксація тривалості окремих технологічних операцій у процесі*

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вільного кування. Для формування повної картини технологічного процесу та порівняння фактичних даних з плановими було застосовано аналіз технологічної документації.

Методи обробки та аналізу даних дозволили розрахувати коефіцієнт виконання норм часу. Цей комплекс методів дозволив не лише кількісно оцінити витрати часу, але й якісно проаналізувати організацію та технологію процесу кування з метою розробки рекомендацій щодо його оптимізації.

Отримані результати. *Проведений хронометраж всіх складових технологічного процесу кування і подальший аналіз виявив тенденції з удосконалення процесу кування високолегованих марок сталей..*

Наукова новизна. *Пооопераційний хронометраж процесу кування поковок супроводжувався аналізом особливостей технологічного процесу, обладнання, що застосовувалося, маси злитка і маси готової поковки, робочих записів, що виконувалися технологічним персоналом в картах кування по факту виконання процесу.*

Практична цінність. *Отримані результати хронометричного дослідження існуючого технологічного процесу кування крупних злитків на гідропресах дають можливість виявити та застосувати технічні рішення для зниження ресурсовитрат.*

Ключові слова: *напружено-деформований стан металу, високолегована сталь, кування, гідравлічний прес, хронометраж операції, ресурсозберігаючі технології.*

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