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Die steel for hot deformation of copper and copper alloys

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Abstract. The possibility of using die steels (4Kh3N5M3F and 4Kh4N5M4F2) with adjustable austenitic transformation during operation for a wide range of operating temperatures (below the critical point A_1 and above the critical point A_3) is shown for hot deformation of M1 copper (up to 630 °C) and MNZh5-1 copper-nickel alloy (900-950 °C) with increased service life. During hot deformation of copper-nickel alloy MNZh5-1, the service life of matrices made of steel with adjustable austenitic transformation 4Kh3N5M3F was increased, compared to steel 3Kh3M3F. The studied forged steel 4Kh4N5M4F2 is characterized by an increase in hardness and strength threshold compared to H13 steel, after the use of extruder wheels (production of more than 60 tons of copper products). In order to facilitate mechanical processing by cutting the work piece during the manufacture of matrices from experimental steels, it was proposed to carry out partial recrystallization, namely, incomplete annealing at a temperature of 750±20 ºC, which made it possible to improve mechanical processing (cutting) for the manufacture of dies and large-sized parts such as wheels extruders.

1 Introduction

Die and matrices for hot deformation of non-ferrous metals and alloys (mainly based on copper) are currently made from steels and alloys. Heat-resistant steels of the austenitic class for the manufacture of die tools have a number of disadvantages that limit their use: low thermal conductivity and a high coefficient of thermal expansion. Their use is also limited due to poor cutting performance and the high cost of alloying elements. Therefore, mainly at enterprises of the corresponding type, die tools of the ferrite class of heat-resistant steel brands are used 5KhNM, 3Kh3M3F, 4KhMF1S, 5Kh5MNFS, 4Kh5W2FS, 4Kh3WMF, 4Kh4WMFS, 4Kh2W2MFS, 3Kh2W8F, 5Kh3W3MFS, 4Kh2W5MF, 4Kh4W4M2K4F, 3Kh3W9F, 6KhW6M5F2, 6Kh4W9M1, 3Kh2W9K5F, Kh2W7M6K12N2, 2Kh6W3M2K8, 3Kh10W7M2K10 etc. for hot deformation of non-ferrous metals and alloys [1, 2]. However, at the operating temperatures of the die tool during hot pressing of non-ferrous metals and alloys, occurs material weakness, which leads to the failure of matrices for hot pressing [3]. Under high operating temperature conditions of 900-1000 °C during hot pressing of a copper-nickel alloy, die steels of the ferritic class have a low service life. In addition, it is of interest to increase the service life of the die tool for hot pressing at the operating temperature of copper (beyond 600 °C) and copper-nickel alloy (beyond 900 °C).

The choice of die steel with control of austenitic transformation during operation (RAPE) for matrices of hot deformation of copper alloys was previously considered by Ukrainian and Russian scientists (Ozerskyi O. D., Kruglyakov A. A., Lebedeva N. V., Perepiolkina M. M., Grabovsky V. Ya., Nguyen Xuan Hoan) [4-8]. They achieved a significant increase in matrix stability during operation at temperatures of 900 °C. It was established that under the influence of high temperatures and a certain load (pressure) during each cycle of pressing a copper alloy occurs plastic deformation of the surface layer of the tool. Accumulation of such deformation does not strengthen the strength of steel with a bcc lattice, but it can strengthen steels with an fcc lattice. That is, in the process of work (hot deformation), die steels in the austenitic state must have increased thermal stability of supercooled austenite with short-term cooling of the tool to 300-400 °C. However, a number of practical works established unsatisfactory cutting of blanks for the manufacture of matrices after steel annealing. During heat treatment in the process of recrystallization (full annealing), a structure with lamellar pearlite is obtained, the grain size of which corresponds to 1-2 points (according to GOST 5950-73), and carbides $M_{23}C_6$, M_6C and MC account for an average of 10 % by volume 'emu. In the future, after mechanical processing of the workpiece and manufacturing of the die tool, thermal strengthening (quenching and tempering) is carried out. After quenching of die steel to a martensitic structure, along with cementite (Fe_3C) are formed carbides of the M_6C and MC types. Annealing of die steels for hot deformation is carried out to increase secondary hardness, during annealing; carbide phases of the MC and M_2C type are formed. Die steels for hot deformation are tempered to hardness of 45-50 HRC, and for die-casting molds, non-ferrous alloys are tempered to a

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hardness of 40-45 HRC. To increase the impact toughness, retempering is carried out, choosing a temperature 30-40°C lower than the first tempering. Production of tool steel from RAPE by traditional casting technology is energy-intensive and includes: full annealing at the temperature of 860 °C, tempering at the temperature of 680 °C, forging blanks at the temperature above 1100 °C, tempering at the temperature range 560–620 °C [4, 8]. Thus, it is advisable to use the technology of obtaining ingots by electroslag remelting, in which the high rate of crystallization of the supercooled melt will contribute to the reduction of the coarse form of the carbide eutectic of the dendritic structure, which will allow the development of a simplified mode of thermo-deformation processing of steel.

Die steels with high cobalt content such as 2Kh6W3M2K8, Kh2W6M6K12N2, etc. have the highest heat resistance. in which the main strengthening phase is intermetallics of the type $(Fe,Co)_2W$ and $(Fe,Co)_7W_6$ (provide operating temperatures above 750 °C) [5]. They are released at higher tempering temperatures (600-650 °C) and have higher stability compared to MC and M_2C carbides. That is, the hardness of 40 HRC remains after heating to 750 °C. It is shown that increasing the amount of cobalt in the die steel composition up to 15 % increases its secondary hardness by 2-3 HRC and heat resistance by 10-20 °C, but the cost of these steels is very expensive. Depending on the brand of deforming alloy, the heating temperature of the surface layer of the die tool steel can vary from quite moderate (400-600 °C) to extremely high (700-1000 °C). At working temperatures higher than 650 °C, even the most heat-resistant steels (GOST 5950-73) are intensively exchanged, which is the main reason for the rapid failure of the tool. Such a situation requires the search for another class of steels. A new class of steels was proposed, which at room temperature belong to the ferritic class, and at the operating temperature they pass into the austenitic region. Such steels were called RAPE [5]. For the manufacture of matrices for hot pressing of copper-nickel alloys, die steel from RAPE was used, which is more stable in the process of operation at working temperatures above the critical point A_3 compared to steels based on ferrite. The additional introduction of the nickel alloying element into the ferrite-based steel led to a decrease in the critical points A_3 and A_1 [9]. In such steels, during operation at high temperatures, an austenite structure is formed and high service properties are maintained. But when using these steels for the manufacture of molds and matrices for hot deformation of non-ferrous metals and alloys, optimal heat treatment stages were not established. The proposed work is devoted to the study of the properties and phase-structural state of die steels of the 4Kh3N5M3F and 4Kh4N5M4F2 brands (obtained by electroslag remelting technology) and after heat treatment. For the first time, a research and industrial test of matrices made of RAPE steel, which were not subject to plastic deformation (forging) and were obtained by the technology of electroslag remelting, was carried out. Further thermal strengthening of the steel (quenching and tempering) while optimizing the heat treatment stages formed the necessary phase-structural state, which ensured the required level of heat resistance and mechanical properties in the operating temperature range. For the production of large wheel-type parts from extruders for hot deformation of copper, thermo-deformation treatment (forging) was developed and optimization of the heat treatment modes of 4Kh4N5M4F2 steel was carried out while ensuring an increase in mechanical and operational properties. Today, the effectiveness of advanced methods of precision forming, both hot three-dimensional forming and hot deformation, depends on the stability of the tool. For die steels of hot deformation, the actual tasks are to reduce their cost price, increase heat resistance, expand the working operational temperature range and increase the operational resource.

For steel 4Kh3N5M3F (without forging technology), the optimal quenching and tempering regimes correspond to 1030±10 °C and 590±10 °C, respectively. To increase the heat resistance of the studied steel, it was decided to adjust the chemical composition, which corresponded to the 4Kh4N5M4F2 brand (Table 1). And also increase the tempering temperature of the studied steel before primary recrystallization. It was established that the optimal tempering temperature of 4Kh4N5M4F2 steel (forging and without forging technology) is 1100±10 °C and tempering is 590±5 °C [10-12]. Primary recrystallization of steel occurs at the temperature of 1110 °C. It was established that the heat resistance of the investigated steel (without forging technology) 4Kh4N5M4F2 increased by 30 °C (at 650 °C, HRC 40 at room temperature) and increased by 10 °C of forged steel 4Kh4N5M4F2 (at 630 °C, HRC 40 at room temperature) compared to steel 4Kh3N5M3F. In the table 2, the properties of 4Kh4N5M4F2 steel (without forging treatment) are given after full annealing according to the developed mode and step annealing according to the mode that was developed for 4Kh2N5M3K5F steel (EP-930), fig. 1 a (technological operations 2 and 3). At the same time, sufficiently high strength characteristics of 1390-1400 MPa were obtained (Table 2). With incomplete annealing at a temperature of 750±20 °C, the strength and yield thresholds of the studied cast steel 4Kh4N5M4F2 were 900 and 800 MPa, respectively, Fig. 1 b (technological operation 2), and table 2. Relative elongation and contraction were 15 and 12 %, respectively. The impact viscosity (CS) was equal to 180 J/cm^2. The proposed mode of incomplete annealing at a temperature of 750±20 °C made it possible to increase the impact toughness by three times, reduce the hardness by 5 HRC, and lower the strength threshold by 500 MPa compared to the properties of EP-930 RATE steel, heat-treated according to the mode proposed by Professor Ozerskyi O. D. and his students (fig. 1 technological operations 2 and 3). However, the properties of forged steel 4Kh4N5M4F2 were much higher than the properties of cast steel and were: strength threshold – 1190-1200 MPa, yield threshold – 1050-1060 MPa, hardness 38-39 HRC with reduced impact viscosity (130 J/cm^2). However, despite the increase in strength and hardness of the experimental forged steel, the workpieces for the production of large-sized parts were satisfactorily processed by cutting.

Table 1. Chemical composition of the studied steels.

Brand steel	*Content of elements (mass fraction, %)*						
	C	*Cr*	*Ni*	*Mo*	*V*	*Si*	*Mn*
*	0,40-0,44	2,80-3,00	4,70-5,50	2,44-2,60	1,34-1,36	0,34-0,35	0,40-0,50
**	0,40-0,42	3,80-3,90	5,00-5,10	3,70-3,80	1,70-1,80	0,072-0,075	0,23-0,24

**- 4Kh3N5M3F, **- 4Kh4N5M4F2*

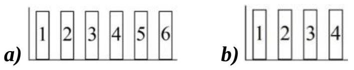


Fig. 1. Schemes of technological operations of steel processing 4Kh3N5M3F: a – according to the technology proposed by the authors A. D. Ozerskyi, Nguyen Xuan Hoan (1 – obtaining ingots according to the traditional casting technology, 2 – annealing at a temperature of 860 ºC with subsequent cooling to 350 ºC, 3 – annealing at a temperature of 680 ºC with subsequent cooling to 400 ºC, 4 – forging at 1180 ºC, 5 – tempering at 1020±10 ºC, 6 – tempering at 570±10 ºC); b – the proposed technology (1 – production of ingots by electroslag remelting, 2 – annealing at 750±20 ºC, 3 – tempering at 1030±10 ºC, 4 – tempering at 590±10 ºC).

Table 2. Mechanical properties of 4Kh4N5M4F2 steel after annealing.

Tempera-ture, °C	*σ_B, MPa*	*$\sigma_{0,2}$, MPa*	*φ, %*	*ψ, %*	*KC, J/cm^2*	*Hardness, HRC*
860±20* and 350±20*	1390-1400	1350-1360	11-12	10-11	50-60	37-38
750±20*	900-910	800-810	14-15	11-12	170-180	32-33
750±20**	1190-1200	1050-1060	21-22	5-6	120-130	38-39
*Note: * - cast, ** - forged*						

2 Objects and research methods

During the production of 4Kh3N5M3F steel, in order to obtain the required chemical composition, the developed ligature of the Fe–Ni–Mo–V–Mn system, which was produced at the Frantsevich Institute for Problems in Materials Science, NAS of Ukraine. The ligature was obtained in an induction furnace and the liquid metal was poured into the mold. The temperature of the metal in the furnace before release was 1550 °C. The duration of refining did not exceed 20 minutes. Castings were obtained by electroslag remelting in a mold (Fig. 2 a, b) and subjected to incomplete annealing at a temperature of 750±20 °C. The chemical composition of the steel corresponded to the 4Kh3N5M3F (Table 1).

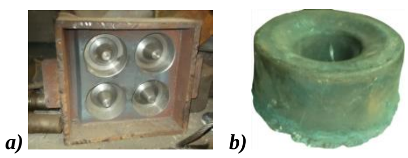


Fig. 2. Steel 4Kh3N5M3F: a – form for obtaining four ingots by electroslag remelting; b – ingot (weight 15 kg).

3 Results and discussion

It should be noted that energy-intensive technological processes (forging and annealing) were not carried out during the manufacture of matrices in comparison with the developed technology presented by Professor Ozerskyi (Fig. 1 a, b). In addition, the main achievement of the work was that annealing (partial recrystallization) of steel was carried out, in which the heat treatment technology was more optimal and less energy-intensive than was proposed by this author. The paper shows that for pre-eutectoid alloy steel 4Kh3N5M3F, during partial recrystallization, spheroidizing carbide component of the pearlite-sorbide structure was created in the structure, which contributed to the improvement of the mechanical processing of the workpiece for the manufacture of matrices. The hardness of steel after heat treatment was determined by the Rockwell method on the TK-2 device (GOST 9013–73) and was 32 HRC.

At the PJSC "Artemivsk Non-ferrous Metals Processing Plant" (Bakhmut, Ukraine) dies made of 3Kh3M3F steel (GOST 5950–2000) are used for die tools. Such steel is used for the manufacture of matrices for hot deformation on crank presses and horizontal forging machines. As a rule, a small tool made of this steel undergoes intense cooling during operation. It is also used for the production of molds for pressure casting of copper alloys. For long-term technological processes of hot pressing (operating temperature 850–950 °C) of ingots made of copper-nickel alloy of the MNZh 5-1 brand and the production of pipes, matrices made of steel with RAPE (4Kh3N5M3F) were used. Deformation of the MNJ5-1 alloy at a heating temperature above 700 °C (critical point A_1) and below 850 °C (critical point A_3) is undesirable, since in this temperature range the process of recrystallization occurs, which was shown when studying the dependence between the phase the structural state (α–Fe and γ–Fe) of the 4Kh3N5M3F steel and the hardness value (Fig. 3, Fig. 4) [13]. The dependence of the amount of austenite on the heating temperature in the temperature range from 20 to 800 °C has a nonlinear character close to exponential (Fig. 3). As the temperature increases, the amount of the austenite component increases. This regularity made it possible to confirm that the austenite structure is preserved during the operation of the die tool above 850 °C. As a result of the analysis, it was established that with increasing temperature, the amount of ferrite phase decreases and the amount of austenite increases. At a temperature of 800 °C, the amount of austenite is 97 %. The conducted high-temperature X-ray phase analysis confirmed the correctness of the determination of the critical points A_1 = 700 °C and A_3 = 850 °C for 4Kh3N5M3F steel, which were previously determined by the method of dilatometric analysis [13-15].

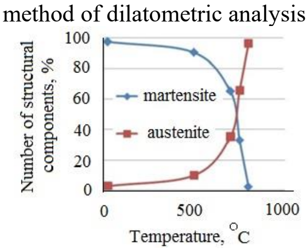


Fig. 3. Change in the amount of austenitic and martensitic components depending on the temperature of hardened steel 4Kh3N5M3F.

The paper shows that the tempering temperature of steel (1030±10 °C) taking into account the tempering at 580±5 °C (cooling in air) is sufficient, since the heat resistance of steel is 44 HRC (Fig. 4). Above the temperature of 620 °C, steel weakens, since the hardness is below 40 HRC (at room temperature), fig. 4.

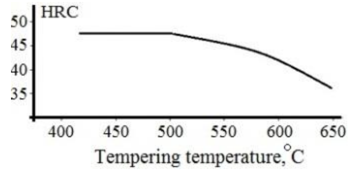
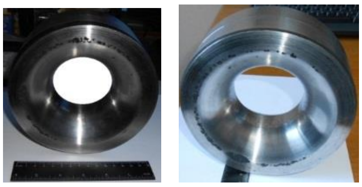


Fig. 4. Dependence of the hardness of cast blanks of die steel 4Kh3N5M3F, obtained by electroslag remelting, hardened at 1030±10 ºC, on the tempering temperature.

Thus, thanks to the optimized heat treatment regimes, the studied steel (without forging treatment) can be used for the manufacture of die tools for hot pressing of non-ferrous metals and alloys.

At the PJSC "Artemivsk plant for non-ferrous metal processing" (Bakhmut, Ukraine), experimental and industrial testing of matrices (Fig. 5 a, b) made of cast steel 4Kh3N5M3F for the manufacture of pipes with a diameter of Ø 67±0.1 mm with copper -nickel alloy of the MNZh5-1 grade at the deformation temperature of 850–950 °C. An ingot with a diameter of 220 mm, a length of 370 mm, and a weight of 120 kg was used as the starting blank. In order to ensure operation in the temperature range of 850–950 °C and at the same time the tool worked in the austenitic region, it was established that it is necessary to preheat the matrix to a temperature of 350 °C, and during operation the temperature of its working part was heated above 850 °C.



a *b*

Fig. 5. Matrix from cast billets of die steel 4Kh3N5M3F, after hot deformation of a copper-nickel alloy of the MNZh5-1 brand (PJSC "Artemivsky Plant for Processing of Non-ferrous Metals", Bakhmut, Ukraine), dimensions: a – diameter; b – is the thickness.

A total of 7 matrices were used. An average of 20 tons of copper alloy was pressed on each of them. Comparative analysis of matrices for hot deformation of copper-nickel alloy MNZh 5-1 in the manufacture of pipes showed that the use of cast steel of the 4Kh3N5M3F grade increased the service life by three times compared to forged steel of the 3Kh3M3F grade. In addition, the overall stability of the matrix made of steel with RAPE increased by 5–6 times when it was further used for a larger pipe diameter, by refining the hole of the matrix and carrying out heat treatment (quenching and tempering).

For the production of large-sized parts such as extruder wheels from 4Kh4N5M4F2 steel from the obtained ingots by electroslag remelting, it is necessary to use a technological operation – forging at a temperature of 1160±20 °C (Fig. 6). It was established that at tempering temperatures >1110 °C primary recrystallization of steel from RAPE (4Kh4N5M4F2) takes place and, as a result, its impact toughness decreases intensively (up to 20 J/cm^2). Further tempering of steel hardened from a temperature of 1100±5 °C with isothermal holding for 4 hours at a tempering temperature of 590±5 °C was used for 47- and 59-kilogram wheels (extruders), fig. 7 a, b.

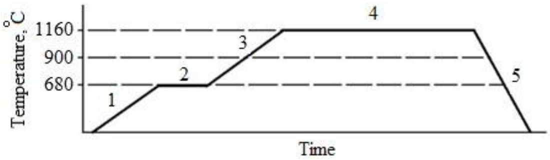


Fig. 6. Technological diagram of the forging process of die steel 4Kh4N5M4F2 obtained after electroslag remelting (1 – heating to 10 °C/min; 2 – isothermal holding for 1 h; 3 – heating to 10 °C/min; 4 – isothermal holding for 3.5 h 5 – air cooling, taking into account forging at a temperature of 900 °C).

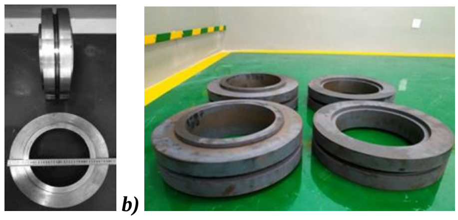


Fig. 7. Details (extruder wheels): a, b – weighing 47 and 59 kg, dimensions 400 mm in diameter, 90 and 120 mm thick, made of 4Kh4N5M4F2 steel, manufactured by Futec Co., Ltd (Ninghai County, Zhejiang Province, China); a – mechanically processed part after annealing; b – after cooking and cooling.

The proposed optimal mode of heat treatment (quenching and tempering) makes it possible to successfully operate steel 4Kh4N5M4F2 with RAPE at temperatures < 630 °C (lower than the critical temperature A_1 for this steel). When the working temperature is increased to 640 °C and higher in RAPE steel processed according to this heat treatment regime, carbon is released from martensite in the form of rhombic carbide of the Me_7C_3 type with lattice periods a = 4.537 Å; b = 6.892 Å; c = 11.91 Å [16], which is accompanied by a decrease in hardness (below 40 HRC at room temperature) and steel strength.

After operation of parts for hot deformation of M1 grade copper (GOST 859-2014) from forged steel 4Kh4N5M4F2 and forged steel H13, samples were cut from them and their properties were determined. Extruder wheels made of the studied steel 4Kh4N5M4F2 did not overheat above a temperature of 630 °C in the process of hot deformation of copper. The confirmation of which is the determination of the mechanical properties (at room temperature) of the studied steel. It is shown that at a tempering temperature of 630 °C, the hardness of steel decreases and is 40 HRC (after quenching 1100±5 °C and tempering 590±5 °C), as well as after quenching 1100±5 °C, tempering 590±5 °C with subsequent heating of the tool to at a temperature of 630 °C at which the hardness was 40 HRC, the strength threshold was up to 1300 MPa and the impact toughness was up to 60 J/cm^2 (Fig. 8).

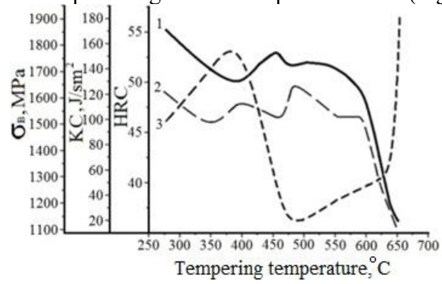


Fig. 8. Dependence of the mechanical properties of forged steel 4Kh4N5M4F2 on heat treatment: quenching at a temperature of 1100±5 ºC, tempering at 590±5 ºC, subsequent heating

(tempering) at temperatures from 275 to 650 ºC (1 – hardness, HRC; 2 – strength threshold, MPa; 3 – impact viscosity, J/cm^2).

It was established that the strength and hardness of the 4Kh4N5M4F2 forged steel was higher than that of the H13 forged steel, but the impact toughness of the tested steel was two times lower. Its value of 90-140 J/cm^2 is actually optimal for die steels during hot deformation (GOST 5950-2000), table. 3.

Table 3. Mechanical properties of steels after operation of extruder wheels (hot deformation of copper).

Brand steel	σ_B, MPa	KC, J/cm^2	Hardness, HRC
H13 (forged) *	1350-1400	250-260	41,5-42,5
4Kh4N5M4F2 (forged)	1580-1640	90-140	47,5-48,5

4 Conclusion

The paper shows the possibility of using die steel 4Kh4N5M4F2 for hot deformation of copper and copper alloy in a wide range of operating temperatures with increased service life compared to traditional die steels used at enterprises. Steel 4Kh3N5M4F2 (without forging treatment) for hot deformation of copper-nickel alloy MNJ5-1 (above the critical point A_3 of this steel) and forged steel 4Kh3N5M3F for hot deformation of copper (below the critical point A_1 of this steel).

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