ТЕХНОЛОГІЇ ОТРИМАННЯ ТА ОБРОБКИ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ

TECHNOLOGIES OF OBTAINING AND PROCESSING OF CONSTRUCTION MATERIALS

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Volodymyr Grabovskyi	Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Physical Materials Science, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: vladimirgr45@ukr.net*, ORCID: 0000-0003-0936-6132
Igor Bilonik	Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Integrated Welding Technologies and Structural Modelling, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: bilonikim@gmail.com*, ORCID: 0000-0002-3873-5307
Anatoliy Ershov	Doctor of Technical Sciences, Professor, Professor of the Department of Physics, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: ershov@zntu.edu.ua*, ORCID: 0000-0003-0878-6434
Olena Lysytsya	Senior Lecturer, Department of Physical Materials Science, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: ov_li@i.ua*, ORCID: 0000-0002-9588-245

DETERMINATION OF TEMPERATURE REGIMES FOR HOT DEFORMATION AND ANNEALING OF NEW 4Kh3N3G7M7F STAMPING STEEL WITH CONTROLLED AUSTENITIC TRANSFORMATION DURING OPERATION AND DISPERSION HARDENING

Purpose. *Determination of heating modes that ensure high technological plasticity during hot pressure treatment and the lowest possible hardness after annealing of new 4Kh3N3G7M7F stamping steel with controlled austenitic transformation during operation and dispersion hardening.*

Research methods. *Torsion and impact bending tests. Hardness measurement. Optical microscopy. X-ray structural analysis.*

Results. *According to the results of torsion and impact bending tests of 4Kh3N3G7M7F steel in the temperature range of 900...1225 °C, it was found that the obtained dependencies have the form of curves with a maximum in the temperature range of 1150...1175 °C at a number of twists about 5 and impact toughness of about 92 J/cm*^{2}*. The torque decreases monotonically as the temperature increases (from 2590 N·m at 900 °C to 739 N·m at 1225 °C). Based on the obtained data, the recommended temperature regime for hot pressure treatment of the steel under study is such that the maximum heating temperature of the billets (ingots) should not exceed 1175 °C and not be lower than 950 °C. After forging and cooling in air, the steel has a bainite-martensite structure with a hardness of 44 HRC.*

Based on the results of the effect of full two-stage and incomplete annealing on the reduction of hardness, it was established that the dependence of hardness on annealing in the temperature range of Ac_1*-*Ac_3 *has the form of a curve with a minimum. Full annealing of the studied steel reduces the hardness to 35 HRC and is recommended to be performed according to the following mode: 800 °C, 2 hours, cooling with the furnace + 680 °C, 2 hours, cooling with the furnace. A reduction in steel hardness to 33 HRC is achieved after incomplete annealing at a temperature of 680 °C for 6 hours and cooling with the furnace. After annealing to minimum hardness, 4Kh3N3G7M7F steel acquires a predominantly fine-grained pearlite structure.*

Scientific novelty. *After hot deformation and air cooling, 4Kh3N3G7M7F steel with controlled austenitic transformation during operation and dispersion hardening has a bainite-martensite structure with a hardness of 44 HRC. It has been established that during annealing, the dependence of hardness on the increase in the holding temperature of 4Х3Н3Г7М7Ф steel in the range of* Ac_1*-*Ac_3 *has the form of a curve with a minimum at a temperature of 680 °C. This is explained by a change in the ratio of steel components with the decomposition of the initial bainite-martensite structure and the restoration of this structure during the cooling of the austenite component. In the annealed state, the steel has a predominantly fine-grained pearlite structure.*

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Practical value. *Based on the results of torsion and impact bending tests, it has been determined that the hot pressure treatment temperature of 4Kh3N3G7M7F steel should be within the range of 1150...950 °C. To improve machinability and obtain a more balanced structure, complete and incomplete annealing modes for 4Kh3N3G7M7F steel have been developed, which reduce the hardness value to 33...35 HRC (compared to 44 HRC after hot deformation). The lowest hardness is achieved by incomplete annealing according to the following mode: 680 °C, holding for 6 hours, cooling in the furnace.*

Key words*: 4Kh3N3G7M7F steel, technological plasticity, temperature, annealing, hardness, structure.*

Introduction

The maximum operating temperature of the best heat-resistant martensitic stamping steels is no higher than 700 °C, which is due to the fundamental characteristics of their base structure. At the same time, during hot metal processing under pressure, the heating of the working parts of tools can significantly exceed these temperatures [1]. This has necessitated the search for other types of stamping materials for use at high temperatures. In particular, steels and alloys based on a BCC crystal lattice with dispersion hardening are proposed as substitutes for standard stamping steels [2–4]. However, their widespread use is limited by their cost and poor machinability [5]. These shortcomings are largely eliminated in new stamping steels with Continuous Annealing Treatment (CAT), the nature and development of which are discussed, in particular, in [6–15]. They have an FCC crystal lattice at room temperature, which gives them satisfactory machinability, and acquire an BCC crystal lattice when heated above 500…600 °C, which increases their resistance to high-temperature embrittlement. This is achieved by lowering their critical points by 200…300 °C compared to standard heat-resistant stamping steels. As a result, steels with CAT offer advantages for the manufacture of pressing tools with operating temperatures above 700 °C. An additional increase in the high-temperature strength of such steels is achieved due to their dispersion hardening after quenching and ageing. A prerequisite for the dispersion hardening of steels with CAT is that after quenching (treatment with a solid solution), they must have a predominantly austenitic rather than martensitic structure [8, 9].

As a result of the search for effective alloying, a new stamping steel with CAT grade 4Kh3N3G7M7F [10] has been developed, which is capable of strengthening by dispersion hardening due to the precipitation of intermetallic particles of the Fe_2Mo type Laves phase and VC type carbides. Its strengthening heat treatment consists of quenching (treatment in a supersaturated solid solution) from a temperature of 1150 °C and subsequent ageing at 725 °C for 2 hours. This provides a significant increase in the high-temperature (750 °C and above) strength of this steel – 2…3 times compared to heat-resistant serial martensitic stamping steels. It has been established [10] that in order to maintain its advantages, 4Kh3N3G7M7F steel must have the following component content limits (in % by mass): 0,39...0,46 C; 2,7...3,6 Cr; 2,7...3,5 Ni; 6,1...6,9 Mn; 6,3...7,1 Mo; 1,1...1,8 V; 0,25...0,36 Si; Fe – the rest. The production and use of 4Kh3N3G7M7F steel requires knowledge of the correct temperature regimes for hot pressure treatment and annealing. The temperature range for heating billets during hot pressure treatment must ensure satisfactory deformability of steels and technological plasticity to prevent the formation of cracks during deformation. Determining the annealing regime, which involves obtaining an equilibrium structure with the lowest possible hardness, is important for ensuring satisfactory machining of steel. Usually, for this purpose, an attempt is made to obtain a pearlite-type structure in alloy steels after annealing. Solving this problem for steels with CAT is not easy due to the high stability of supercooled austenite and, accordingly, the complexity of obtaining such an equilibrium structure. All this indicates the need to carry out appropriate experiments to solve such problems.

Purpose of the work

To determine the heating modes that ensure high technological plasticity during hot pressure treatment and the lowest possible hardness after annealing of new 4Kh3N3G7M7F stamping steel with controlled austenitic transformation during operation and dispersion hardening.

Materials and research methods

4Kh3N3G7M7F steel was smelted in an open induction furnace with a capacity of 50 kg and poured into square-section ingots. The alloying element content of the steel melts was within the grade composition specified above.

Samples for torsion and impact bending tests were made from steel ingots. First, the ingots were cut lengthwise into 15 mm thick plates, and then cut into square-section bars with a side length of 15 mm. Samples for torsion and impact bending tests were made from these bars.

In accordance with GOST 3565-80, the torsion test specimens had a diameter of 10 mm and a working length of 100 mm. The nature of the tests was that one end of the specimen was fixed in place, while a pair of forces was applied to the other end in a plane perpendicular to the axis of the specimen. One end of the sample was fixed, while the other rotated at a selected speed. This meant that the second end of the sample was able to perform longitudinal gradual movements, which excluded the possibility of axial tensile stresses forming in the sample. The samples were twisted on a KM-50 testing machine. The tests were performed at a speed of 20 revolutions per minute until the specimens were destroyed. Based on the test results, the number of revolutions until the destruction of the specimens and the corresponding value of the torque M_t were determined.

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The impact bending test was performed on standard Menage specimens with a U-shaped notch with a radius of 1 mm.

To study the annealing modes, the ingots were forged into square-section bars with a side length of 20 mm, which were cooled in air. The bars were cut into cubic samples.

Research results and discussion

When assessing the technological plasticity of 4Kh3N3G7M7F steel, it was taken into account that it was necessary to determine the temperature range of the highest values of plasticity, resistance to destruction and the lowest resistance to high-temperature deformation in order to predict the best deformability during forging or pressing. Torsion and impact bending tests were carried out on samples in the temperature range of 900…1225 °C. The resulting dependencies are shown in Fig. 1. It can be seen that during torsion tests, the value of the torsional moment M_t monotonically decreases as the temperature increases (from 2590 N·m at 900 °C to 740 N·m at 1225 °C), which corresponds to the natural temperature dependence of steel resistance to plastic deformation. The torque M_t decreases most intensively up to a temperature of 1150 °C. The temperature dependence of the number of revolutions has the form of a curve with a maximum in the temperature range 1150...1175 °C at a value of about 5 revolutions. The curve of the temperature dependence of impact toughness has a similar appearance, the maximum value of which (about 92 J/cm^2) corresponds to testing at temperatures of 1100...1150 °C. That is, the best combination of technological plasticity characteristics is achieved when heated to a temperature of 1150 °C. Higher heating temperatures cause structural changes that significantly reduce the technological plasticity of steel and can lead to metal destruction during hot pressure treatment.

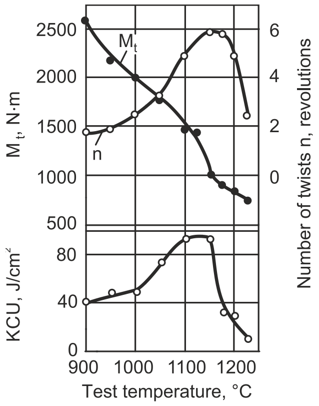

Figure 1. Dependence of torque (M_t), number of twists (n) and impact toughness (KCU) of 4Kh3N3G7M7F steel on test temperature

Thus, based on the results of determining the highest values of the number of twists and impact toughness, the maximum heating temperature of billets (ingots) during hot pressure treatment of 4Kh3N3G7M7F steel should not exceed 1150 °C. At the same time, the torque value is significantly reduced, which ensures good high-temperature deformability of steel. The lower value of the hot deformation temperature is about 950 °C and can be adjusted depending on the power of the stamping equipment and the size of the forgings. Taking into account the obtained results and structural features, the following heating scheme for ingots of new 4Kh3N3G7M7F stamping steel during hot pressure treatment is proposed. First, the blank is loaded into a furnace at a temperature of 800 °C (taking into account that the temperature of Ac_3 = 795 °C) and, after complete heating, is held for 1 hour to complete the polymorphic $\alpha \rightarrow \gamma$ transformation. Next, the blank is heated at a rate of 50 °C per hour to a forging temperature of 1150 °C, held for 1 hour and subjected to forging. The forging completion temperature is not lower than 950 °C. During the forging process, intermediate heating to 1150 °C is possible. The use of this heating scheme ensured the production of high-quality 4Kh3N3G7M7F steel forgings.

Let us consider the results of determining the annealing modes that provide 4Kh3N3G7M7F steel with the lowest hardness values and, accordingly, better machinability. The initial state of processing was forging and air cooling. In this state, the steel had a predominantly bainite-martensite structure, as shown in Fig. 2. The hardness was 44 HRC, which is too high for satisfactory machining of steel.

The study of the effect of different annealing modes on the reduction of the hardness of 4Kh3N3G7M7F steel was carried out taking into account its relatively low critical points: Ac_1 at about 530 °C, Ac_3 at 795 °C , Ar_1 at 220 °C, M_s at 135 °C, M_f – 40 °C. Full annealing of samples was carried out using a two-stage mode with a sequential decrease in temperature, and incomplete single annealing at different temperatures.

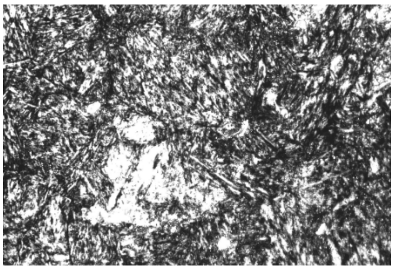

Figure 2. Microstructure of 4Kh3N3G7M7F steel after forging and air cooling

First, the effectiveness of two-stage annealing was investigated. The first annealing corresponded to complete annealing and consisted of heating the samples to temperatures of 800…900 °C (i.e. above Ac_3) with a holding time of 2 hours and cooling with the furnace (100 °C/hour to 300 °C, then in air). This was followed by a second annealing at temperatures ranging from 580 to 730 °C (in the Ac_1–Ac_3 region) with the same holding

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time and cooling as in the first annealing. It was assumed that after the first annealing, the austenitic structure would transform into bainite-martensite, which is due to the high stability of supercooled austenitic steel. The purpose of the second annealing was to break down the bainite-martensite structure, i.e. to obtain a more equilibrium state and, accordingly, lower steel hardness. The results of this experiment are shown in Fig. 3. Each curve corresponds to a specific temperature of the previous first annealing (indicated on the graph). According to the data obtained, the hardness after the first annealing is in the range of 39...41 HRC and increases with higher annealing temperatures. This is explained by the increase in the concentration of carbon and alloying elements in the solid solution due to the more complete dissolution of excess carbide phases with increasing heating temperature.

A typical microstructure after the first annealing (heating above Ac_3 and cooling with the furnace) is shown in Fig. 4, *a*.

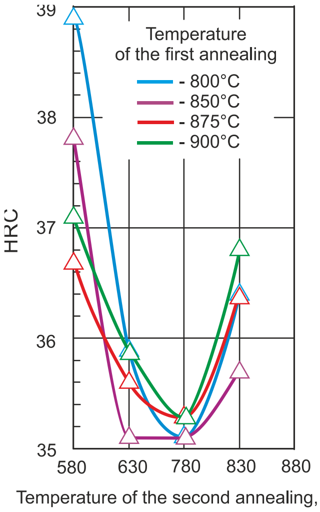
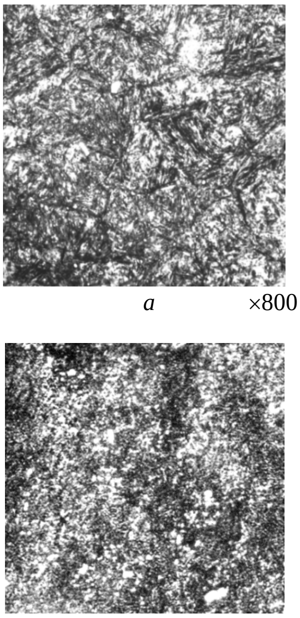


Figure 3. Hardness dependence on the temperature of the second annealing after different temperatures of the first annealing (indicated for each curve in the graph)

It is similar to the microstructure after forging (see Fig. 2), i.e. it is also characterised as bainitic-martensitic, but with a slightly smaller austenite grain size, which is the result of complete recrystallisation during heating.

As can be seen from Fig. 3, all curves of hardness dependence on the temperature of the second annealing have a minimum in the region of 680 °C, which can be explained as follows. The decrease in hardness with an increase in the holding temperature to 680 °C is due to the decomposition of the initial bainite-martensite structure formed after the first annealing. As the temperature increases from 680 °C to 730 °C, the proportion of the austenitic component in the steel increases significantly, and subsequent cooling to room temperature will lead to its transformation according to bainite-martensite kinetics. The increase in hardness due to the formation of such a structure during cooling will prevail over the decrease in hardness due to the decay of the initial bainite-martensite component of the structure. Accordingly, the closer to the temperature Ac_3 (795 °C), the greater the proportion of the bainite-martensite structure in the cooled state, which is characterised by increased hardness.


a ×800

b ×800

Figure 4. Microstructures of 4Kh3N3G7M7F steel after complete step annealing:
a – first annealing at 800 °C; *b* – second annealing at 680 °C

The hardness values in the minimum range for different annealing temperatures are slightly different. The lowest hardness was obtained for samples that were pre-annealed at temperatures of 800…850 °C (average – 825 °C), equal to 35,1 HRC. This is 9 HRC units less than after cooling the forgings in the furnace. The microstructure after such annealing is shown in Fig. 4, *b* and mainly corresponds to fine-grained pearlite formed as a result of furnace cooling of the decomposition products of the initial bainite-martensite structure. There are also areas of bainite-martensite structure formed during the cooling of the austenite component, which occurs when heated above Ac_1, and a small amount of residual austenite. X-ray phase analysis has established that after the second annealing to minimum hardness, the base of the steel is α-iron, and the amount of residual austenite does not exceed 6%. Phase analysis showed the presence of MC and $M_{23}C_6$ carbides in the structure.

Thus, complete annealing (which is usually used to obtain a more perfect structure) to a hardness of 35 HRC is recommended to be performed in a stepwise mode: 825 °C, 2 hours, cooling with the furnace + 680 °C, 2 hours, cooling with the furnace.

Let us consider the results of a study of single annealing for the possibility of reducing the hardness of steel. The change in steel hardness after heating and holding samples in the temperature range of 580...850 °C

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for 2 hours with cooling both in the furnace and in air was investigated. For the selected temperature range, such annealing is considered incomplete. Figure 5 shows that the dependencies obtained for both cooling methods are curves with a minimum at 680 °C, as for complete step annealing. When the heating temperature is increased to 800 °C, the hardness reaches its maximum value and then stops increasing. This is due to the fact that above ac$_3$ (795 °C), the steel becomes completely austenitic, and when cooled, it acquires a bainite-martensite structure. The presence of a minimum on the curves is explained in the same way as in the case of the complete step annealing considered above. Naturally, the cooling curve with the furnace is lower than that with air cooling. Accordingly, if in the first case the minimum hardness value is 34,7 HRC, then in the second case it is 35,6 HRC.

The possibility of achieving even lower hardness after single annealing by increasing the holding time to 6 hours at temperatures around 680 °C, i.e. 630...700 °C, was also investigated. The results obtained are shown in Table 1.

It can be seen that as the holding time increases, the hardness values at all temperatures decrease slightly. Moreover, for all annealing temperatures after cooling in the furnace, the hardness is 0,8...1,5 HRC units lower compared to air cooling. The lowest hardness of 32,5 HRC is achieved by annealing at 680 °C for 6 hours and cooling in the furnace. This incomplete annealing mode can be recommended for 4Kh3N3G7M7F steel to ensure better machinability. The microstructure after such annealing is similar to that shown in Fig. 4, *b*, i.e. It is mainly fine-grained pearlite with areas of bainite-martensite and residual austenite. The difference is the larger grain size of austenite and the heterogeneity of the structure, which is characteristic of annealing when heated to temperatures of incomplete recrystallisation.

Thus, to reduce the hardness of the new 4Kh3N3G7M7F steel after hot deformation, annealing can be performed, depending on the complex requirements for structure and hardness, either with complete (full annealing) or partial (incomplete annealing) recrystallisation.

Full annealing, which is usually used to obtain a more perfect structure, is performed in a stepwise mode: 825 °C, 2 hours, cooling with the furnace + 680 °C, 2 hours, cooling with the furnace. The hardness after such annealing is about 35 HRC. Incomplete annealing reduces the hardness to 33 HRC and is performed according to the following mode: 680 °C, 6 hours, cooling with the furnace.

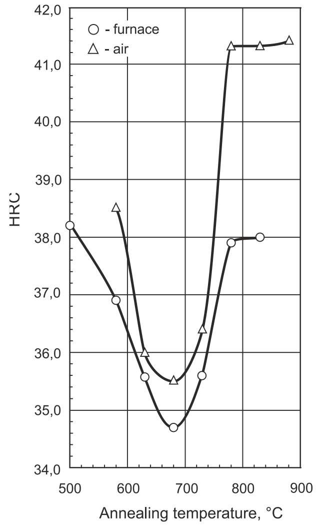

Figure 5. Effect of annealing temperature (2 hours holding time) on hardness after different cooling of steel

Table 1 – Hardness values of 4Kh3N3G7M7F steel after different temperatures and times of incomplete annealing

Annealing temperature, °C	Exposure time, hours	Cooling method	Hardness, HRC
650	2	with a furnace	34,5
		in the air	35,2
	4	with a furnace	34,1
		in the air	34,5
	6	with a furnace	32.8
		in the air	33,5
680	2	with a furnace	33,8
		in the air	35,1
	4	with a furnace	32,6
		in the air	34,3
	6	with a furnace	32,5
		in the air	33,3
700	2	with a furnace	34,5
		in the air	35,1
	4	with a furnace	33,5
		in the air	34,7
	6	with a furnace	33,1
		in the air	34,0

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Conclusions

During hot pressure treatment of new 4Kh3N3G7M7F stamping steel with CAT and dispersion hardening, the maximum heating temperature of billets (ingots) should not exceed 1150…1175 °C. This temperature corresponds to the maximum values of the technological plasticity of steel according to the results of torsion and impact bending tests and a significant reduction in torque. The lower value of the hot deformation temperature is recommended to be at least 900 °C.

After hot deformation and air cooling, 4Kh3N3G7M7F steel has a bainite-martensite structure with a hardness of 44 HRC. Full annealing of the tested steel reduces the hardness to 35 HRC and is recommended to be performed according to the following regime: 850 °C, 2 hours, cooling with the furnace + 680 °C, 2 hours, cooling with the furnace. A reduction in steel hardness to 33 HRC is achieved after incomplete annealing according to the following regime: 680 °C, 6 hours, cooling with the furnace. The dependence of hardness on annealing in the temperature range Ac_1–Ac_3 has the form of a curve with a minimum, which is due to a change in the ratio of particles of the bainite-martensite structure that disintegrated and formed during the cooling of austenite. In the annealed state, 4Kh3N3G7M7F steel has a predominantly fine-grained pearlite structure at minimum hardness.

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ВИЗНАЧЕННЯ ТЕМПЕРАТУРНИХ РЕЖИМІВ ГАРЯЧОЇ ДЕФОРМАЦІЇ ТА ВІДПАЛУ НОВОЇ ШТАМПОВОЇ СТАЛІ 4Х3Н3Г7М7Ф З РЕГУЛЬОВАНИМ АУСТЕНІТНИМ ПЕРЕТВОРЕННЯМ ПРИ ЕКСПЛУАТАЦІЇ ТА ДИСПЕРСІЙНОМУ ТВЕРДІННЮ

Володимир Грабовський	канд. техн. наук, доцент, доцент кафедри фізичного матеріалознавства Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: vladimirgr45@ukr.net*¸ ORCID: 0000-0003-0936-6132
Ігор Білоник	канд. техн. наук, доцент, доцент кафедри «Інтегровані технології зварювання та моделювання конструкцій» Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: bilonikim@gmail.com,* ORCID: 0000-0002-3873-5307
Анатолій Єршов	д-р техн. наук, професор, професор кафедри фізики Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: ershov@zntu.edu.ua,* ORCID: 0000-0003-0878-6434
Олена Лисиця	старший викладач кафедри фізичного матеріалознавства Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: ov_li@i.ua,* ORCID: 0000-0002-9588-2450

Мета роботи. *Визначення режимів нагріву, що забезпечують високу технологічну пластичність при гарячій обробці тиском та якомога меншу твердість після відпалу нової штампової сталі 4Х3Н3Г7М7Ф з регульованим аустенітним перетворенням при експлуатації та дисперсійному твердінню.*

Методи дослідження. *Випробування на кручення та ударний згин. Вимірювання твердості. Оптична мікроскопія. Рентгеноструктурний аналіз.*

Отримані результати*. За даними випробувань сталі 4Х3Н3Г7М7Ф на кручення та ударний згин в інтервалі температур 900…1225 °С встановлено, що отримані залежності мають вигляд кривих з максимумом в області температур 1150…1175 °С при числу обертів біля 5 та ударної в'язкості біля 92 Дж/см^2. Величина крутного моменту монотонно зменшується по мірі зростання температури (від 2590 Н·м при 900 °С до 739 Н·м при 1225 °С). Відповідно отриманим даним рекомендовано температурний режим гарячої обробки тиском дослідженої сталі, за яким максимальна температура нагріву заготовок (зливків) повинна бути не вище 1175 °С та не нижче 950 °С. Після кування і охолодження на повітрі сталь має бейнітно-мартенситну структуру з твердістю 44 HRC.*

За результатами впливу на зниження твердості повного двоступеневого та неповного відпалів встановлено, що залежність твердості від відпалу в області температур Ac_1-Ac_3 має вигляд кривої з мінімумом. Повний відпал дослідженої сталі забезпечує зниження твердості до 35 HRC і рекомендовано виконувати за таким режимом: 800 °С, 2 години, охолодженні з піччю + 680 °С, 2 години, охолодженні з піччю. Зниження твердості сталі до 33 HRC досягається після неповного відпалу при температурі 680 °С протягом 6 годин і охолодження з піччю. Після відпалу на мінімальну твердість сталь 4Х3Н3Г7М7Ф набуває переважно структуру дрібнодисперсного зернистого перліту.

Наукова новизна. *Після гарячої деформації та охолодження на повітрі сталь 4Х3Н3Г7М7Ф з регульованим аустенітним перетворенням при експлуатації та дисперсійним твердінням має бейнітно-мартенситну структуру з твердістю 44 HRC. Встановлено, що при відпалі залежність твердості від зростання температури витримки сталі 4Х3Н3Г7М7Ф в інтервалі Ac_1-Ac_3 має вигляд кривої з мінімумом при температурі 680 °С. Пояснюється це зміною співвідношення складових часток сталі з розпадом вихідної бейнітно-мартеситної структури та з поновленням такої структури при охолодженні аустенітної складової. У відпаленому стані сталь має переважно структуру дрібнодисперсного зернистого перліту.*

Практична цінність. *За результатами випробувань на кручення та ударний згин визначено, що температура гарячої обробки тиском сталі 4Х3Н3Г7М7Ф повинна знаходитися в межах 1150…950 °С. Для покращення обробки різанням та отримання більш рівноважової структури розроблені режими повного та неповного відпалів сталі 4Х3Н3Г7М7Ф, які знижують значення твердості до 33…35 HRC (порівняно з 44 HRC після гарячої деформації). Найменшу твердість забезпечує неповний відпал за режимом: 680 °С, витримка 6 годин, охолодження з піччю.*

Ключові слова: *сталь 4Х3Н3Г7М7Ф, технологічна пластичність, температура, відпал, твердість, структура.*

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