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The influence of hardening heat treatment modes on the crack propagation resistance of 5H2SMF die steel

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Abstract: In the literature, there are virtually no data on the effect of quenching with holding in the pearlite and bainitic regions and subsequent low and high tempering of different durations on the crack propagation resistance of die steels, and the available data are contradictory. Meanwhile, a "softer" quenching with holding in the intermediate regions reduces significantly the risk of quenching cracks and deformation of dies and die tooling. In this work, samples of 5H2SMF die steel with a sharp notch and artificially induced cracks were subjected to heat treatment, including standard quenching at 910 °C in oil and quenching from 910 °C with steps at 650 °C and 340 °C with different types of tempering (200, 560, 600, and 640 °C) and different durations of time – 1, 3, 5, 7, and 14 h (for 200 °C) in order to increase the crack propagation resistance. The conducted studies allowed identifying that the data on crack propagation resistance after step quenching with holding in the pearlite transformation region and subsequent high tempering at 560, 600 and 640 °C are comparable with standard quenching in oil and high tempering at the same temperatures. The hardness after step quenching in the bainitic transformation region (340 °C) is significantly lower in all cases under different tempering conditions; therefore, it is not possible to compare crack propagation resistance with standard quenching. The optimal holding time (3 and 5 h) from the point of view of increasing crack propagation resistance after standard quenching from 910 °C in oil and low tempering at 200 °C was found.

Keywords: die steel; quenching; tempering; hardness; crack propagation resistance.

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INTRODUCTION

Heat treatment is one of the key processes significantly affecting mechanical properties, therefore the correct choice of the quenching mode, during which the alloying elements are redistributed, the grain size changes, carbides dissolve, etc., ultimately determines the operational properties of steel products.

Step quenching used to reduce quenching stresses and deformation is known from the report "On the Preparation of Steel Armour-Piercing Projectiles" of D.K. Chernov in 1885 [1]. Despite the fact that this method has now been studied quite well, in the literature, there are contradictory data on the influence of step quenching on the mechanical properties of steels after various modes of tempering [2–4]. Step cooling of metastable austenite in the pearlite area without decomposition into a ferrite-carbide mixture led to the discovery of interesting effects [5; 6]. A comparison of conventional quenching with quenching with isothermal holding at 560–680 °C shows that for 6H6M1, 5F3B and 6H6M3F steels, processes leading to an increase in hardness occur in supercooled austenite. These processes are associated with the formation of equilibrium regions of 10–15 Å in size in martensite resulted from step quenching, having an increased content of carbon, vanadium and molybdenum, with the same lattice as the matrix. During subsequent tempering, these microheterogeneities act as nuclei for the formation of carbides, providing them with high dispersion and uniformity of distribution, which leads to an increase in the heat resistance of the dies [5; 7; 8].

A study of the patterns of structural transformations occurring during quenching with holding in the bainitic transformation region of the 30HSNMFB and 30H3N3MFB steels showed that at the early stages of such holding, agglomerates (clusters or mixed zones) of alloying element atoms (vanadium and carbon) are formed by analogy with the processes occurring at the initial stages of aging of many steels [9; 10]. The authors believe that these clusters also contain molybdenum and chromium atoms [9; 11]. The presence of such clusters of atoms exhibits the resistance to destruction and thereby strengthens the steel.

The processes of both high and low tempering of quenched steel occurring at different temperatures have been studied quite well. However, in the literature, there are practically no data on the influence of tempering duration on the properties of steels. A number of studies provide non-monotonic dependencies of mechanical properties on tempering duration [12–14]. The identified non-monotonic, sawtooth nature of the "resistance to crack propagation – time" curves is presented without any comments [14; 15].

5H2SMF die steel is used mainly for the manufacture of hot deformation dies, but since in the low-tempered state the hardness is in the range of 58–60 HRC, it can also be used for cold deformation dies [16; 17]. In this regard, in the presented work, a comparative study of the dependence of the resistance to crack propagation and hardness of 5H2SMF steel after standard quenching (in oil), and quenching with holding in the pearlite and bainitic regions with subsequent low and high tempering, as well as low tempering of different durations, is carried out.

The purpose of this study is to develop hardening heat treatment modes for industrially used 5H2SMF die steel, including quenching with holding in the pearlite and bainitic regions and tempering at different temperatures of different durations, increasing the resistance to crack propagation.

METHODS

For the study, 5H2SMF die steel [18] was selected. The chemical composition of the steel is given in Table 1.

The heat treatment of the studied samples with dimensions of 10×11×55 mm was carried out in salt baths of AO Obukhovski Plant (JSC). Termooil-26 oil was used as a quenching medium. Tests for each heat treatment mode were carried out on 7 samples. Three quenching modes were studied: 1 – 910 °C, 15 min, cooling in oil; 2 – 910 °C, 15 min – 340 °C, 15 min, cooling in oil; 3 – 910 °C, 15 min – 650 °C, 7 min, cooling in oil; subsequent tempering: 200, 560, 600, and 640 °C for 2 h for each quenching mode. A study was conducted as well on the duration of low tempering. The samples after quenching according to the standard mode (910 °C, 15 min, cooling in oil) were subjected to low tempering (200 °C) of different durations: 1, 3, 5, 7, and 14 h.

The blanks of the samples for determining the mechanical properties were prepared with a grinding allowance of 0.5 mm. After quenching, the dimensions were brought to the finished ones (10×10×55 mm), which allowed, excluding the influence of decarburisation occurring during heating for quenching, on the hardness of the samples. The maximum achievable force (P_c) required for complete destruction of the sample during static three-point bending was taken as the evaluation criterion.

The experiment was carried out on samples for impact toughness testing according to KCT with a *V*-shaped notch 1.5 mm deep and a concentrator radius *R* of 0.25±0.025 (GOST 9454-78, Fig. 3). According to clause 1.4 of GOST 9454-78 and clause 1.6 of GOST 25.506-85, a fatigue crack 1.5 mm deep was initiated by the cyclic loading method with a number of cycles of at least 3000 on a Drozdovsky resonant vibrator (Russia). The maximum residual deflection formed when applying a T-type concentrator to the samples did not exceed 0.25 mm.

Static bending tests were carried out on a POWERTEST T testing machine (Spain) (distance between supports is 45 mm) with a loading rate of no more than 2 mm/min.

Due to the fact that when initiating a fatigue crack on a Drozdovsky vibrator, some deviation of the depth from the required one is possible, after testing the fractures of all samples, the total depth of the crack and notch (L_{cr}) was measured using an MPB-2 counting microscope (Russia). The analysis of the obtained experimental data on crack propagation resistance and hardness after various heat treatment modes was carried out taking into account the actual total crack and notch depth. Hardness was measured on a TK-2M hardness tester (Russia).

RESULTS

Hardness and crack propagation resistance after low and high tempering

Table 2 shows that the maximum values of hardness and crack resistance (P_{cr}) after low tempering (200 °C) were obtained after standard oil quenching. Quenching with holding in the pearlite region (mode 3) with an insignificant (by 0.5 HRC) decrease in hardness and a 0.03 mm less total crack and notch depth (L_{cr}) leads to an insignificant (by 64 kN/cm^2) decrease in crack resistance. Crack resistance is maximum after the mode with a step at 340 °C, but at the same time the hardness in the low-tempered state decreases significantly (by 5 HRC), which indicates the occurrence of partial bainitic decomposition.

Hardness after quenching according to mode 3 and tempering at 560 °C has maximum values (49 HRC) with minimum total crack and notch depth (3.16 mm versus 3.4 and 3.34 mm after standard quenching and with holding at 340 °C, respectively), while this mode has minimum values of crack propagation resistance (P_{cr}) (Table 3). Samples

Table 1. *Chemical composition of 5H2SMF [18]*
Таблица 1. *Химический состав 5Х2СМФ [18]*

Steel grade	C, %	Mn, %	Si, %	Cr, %	Mo, %	V, %
5H2SMF	0.56	0.47	0.72	2.48	0.23	0.27

***Table 2.** Maximum (P_{max}), average (P_{av}) and minimum (P_{min}) values of crack propagation resistance, hardness after quenching (HRC_{quen}) and tempering (HRC_{temp}) and total depth of crack and notch (L_{cr}) of 5H2SMF steel quenched by different modes and tempered at 200 °C*

***Таблица 2.** Максимальное (P_{max}), среднее (P_{av}) и минимальное (P_{min}) значение сопротивления развитию трещины, твердость после закалки (HRC_{quen}) и отпуска (HRC_{temp}) и суммарная глубина трещины и надреза (L_{cr}) стали 5Х2СМФ, закаленной по различным режимам, отпуск при 200 °C*

Mode No.	Quenching mode	Crack propagation resistance (P_{cr}), kN/cm^2			Hardness, HRC		Total depth of crack and notch (L_{cr}), mm
		$P_{cr\ max}$	$P_{cr\ av}$	$P_{cr\ min}$	HRC_{quen}	HRC_{temp}	
1	910 °C in oil	735	667	590	61.0	58.5	3.27
2	910 °C – 340 °C in oil	770	727	630	54.0	53.5	3.62
3	910 °C – 650 °C in oil	670	603	500	60.5	58.0	3.24

***Table 3.** Maximum (P_{max}), average (P_{av}) and minimum (P_{min}) values of crack propagation resistance, hardness after quenching (HRC_{quen}) and tempering (HRC_{temp}) and total depth of crack and notch (L_{cr}) of 5H2SMF steel quenched by different modes and tempered at 560 °C*

***Таблица 3.** Максимальное (P_{max}), среднее (P_{av}) и минимальное (P_{min}) значение сопротивления развитию трещины, твердость после закалки (HRC_{quen}) и отпуска (HRC_{temp}) и суммарная глубина трещины и надреза (L_{cr}) стали 5Х2СМФ, закаленной по различным режимам, отпуск при 560 °C*

Mode No.	Quenching mode	Crack propagation resistance (P_{cr}), kN/cm^2			Hardness, HRC		Total depth of crack and notch (L_{cr}), mm
		$P_{cr\ max}$	$P_{cr\ av}$	$P_{cr\ min}$	HRC_{quen}	HRC_{temp}	
1	910 °C in oil	1180	1170	1060	62.0	48.5	3.40
2	910 °C – 340 °C in oil	1515	1381	1292	53.5	46.5	3.34
3	910 °C – 650 °C in oil	920	840	730	61.5	49.0	3.16

quenched according to mode 2, compared to standard quenching with a decrease in hardness (by 2 HRC) and a 0.06 mm less total crack and notch depth (L_{cr}), have maximum (more than 200 kN/cm^2 compared to standard quenching) crack propagation resistance (P_{cr}) (Table 3). The hardness after tempering at 600 °C, as in the previous experiment, has maximum values after quenching with a step at 650 °C, but the value of crack propagation resistance (P_{cr}) is minimal (Table 4). The values of crack propagation resistance (P_{cr}) after mode 2 and standard quenching with some decrease in hardness (by 1.5 HRC) at approximately the same total crack and notch depth (3.38 and 3.37 mm) are comparable (2410 and 2420 kN/cm^2, respectively) (Table 4).

After heat treatment according to mode 3, the maximum hardness values (38 HRC) were obtained, while unlike the mode of tempering at 600 °C (Table 4), such a large difference in crack propagation resistance (P_{cr}) is not observed at an equal total crack and notch depth (3.3 mm) compared to standard quenching (Table 5). The decrease in hardness after tempering at 640 °C and quenching according to mode 2 does not increase the value of crack propagation resistance (P_{cr}) compared to standard quenching and quenching according to mode 3, even despite the minimum (3.2 mm) total crack and notch depth (L_{cr}) (Table 5).

Hardness and crack propagation resistance after tempering (200 °C) of different durations

Table 6 shows that increasing the holding time from 1 to 14 h of low tempering leads to an insignificant (by 1.5 HRC) decrease in the hardness of 5H2SMF steel samples.

Tempering for 3 h leads to maximum (667 kN/cm^2) crack propagation resistance (P_{cr}) values at maximum hardness (58 HRC) and maximum (3.37 mm) total crack and notch depth (L_{cr}). With tempering for 5 h, a minimum (55 kN/cm^2) difference can be observed between the maximum and minimum crack propagation resistance (P_{cr}), while for other modes it is more than 135 kN/cm^2. The values of crack propagation resistance (P_{cr}) at equal hardness (57.5 HRC) and maximum (3.37 mm) total crack and notch depth (L_{cr}) are comparable with other modes (Table 6).

Conducting tempering for 1 h leads to minimum values of crack propagation resistance (P_{cr}), which is probably associated with the fact that one-hour tempering does not eliminate the brittleness specific for freshly quenched martensite.

Table 4. *Maximum (P_{max}), average (P_{av}) and minimum (P_{min}) values of crack propagation resistance, hardness after quenching (HRC_{quen}) and tempering (HRC_{temp}) and total depth of crack and notch (L_{cr}) of 5H2SMF steel quenched by different modes and tempered at 600 °C*

Таблица 4. *Максимальное (P_{max}), среднее (P_{av}) и минимальное (P_{min}) значение сопротивления развитию трещины, твердость после закалки (HRC_{quen}) и отпуска (HRC_{temp}) и суммарная глубина трещины и надреза (L_{cr}) стали 5Х2СМФ, закаленной по различным режимам, отпуск при 600 °C*

Mode No.	**Quenching mode**	**Crack propagation resistance (P_{cr}), kN/cm²**			**Hardness, HRC**		**Total depth of crack and notch (L_{cr}), mm**
		$P_{cr\ max}$	$P_{cr\ av}$	$P_{cr\ min}$	HRC_{quen}	HRC_{temp}	
1	910 °C in oil	2600	2420	2120	61.0	43.5	3.37
2	910 °C – 340 °C in oil	2550	2410	2040	54.0	42.0	3.38
3	910 °C – 650 °C in oil	1280	1188	1085	60.5	45.0	3.35

Table 5. *Maximum (P_{max}), average (P_{av}) and minimum (P_{min}) values of crack propagation resistance, hardness after quenching (HRC_{quen}) and tempering (HRC_{temp}) and total depth of crack and notch (L_{cr}) of 5H2SMF steel quenched by different modes and tempered at 640 °C*

Таблица 5. *Максимальное (P_{max}), среднее (P_{av}) и минимальное (P_{min}) значение сопротивления развитию трещины, твердость после закалки (HRC_{quen}) и отпуска (HRC_{temp}) и суммарная глубина трещины и надреза (L_{cr}) стали 5Х2СМФ, закаленной по различным режимам, отпуск при 640 °C*

Mode No.	**Quenching mode**	**Crack propagation resistance (P_{cr}), kN/cm²**			**Hardness, HRC**		**Total depth of crack and notch (L_{cr}), mm**
		$P_{cr\ max}$	$P_{cr\ av}$	$P_{cr\ min}$	HRC_{quen}	HRC_{temp}	
1	910 °C in oil	2600	2451	2100	61.0	36.5	3.3
2	910 °C – 340 °C in oil	2290	2150	2070	53.5	35.0	3.2
3	910 °C – 650 °C in oil	2530	2272	2100	60.5	38.0	3.3

Table 6. *Maximum (P_{max}), average (P_{av}) and minimum (P_{min}) values of crack propagation resistance, hardness after quenching (HRC_{quen}) and tempering (HRC_{temp}) and total depth of crack and notch (L_{cr}) of 5H2SMF steel quenched under the standard mode (910 °C in oil), tempering at 200 °C with different durations*

Таблица 6. *Максимальное (P_{max}), среднее (P_{av}) и минимальное (P_{min}) значение сопротивления развитию трещины, твердость после закалки (HRC_{quen}) и отпуска (HRC_{temp}) и суммарная глубина трещины и надреза (L_{cr}) стали 5Х2СМФ, закаленной по стандартному режиму (910 °C в масло), отпуск при 200 °C разной продолжительности*

Holding time at tempering at 200 °C, h	**Crack propagation resistance (P_{cr}), kN/cm²**			**Hardness, HRC**		**Total depth of crack and notch (L_{cr}), mm**
	$P_{cr\ max}$	$P_{cr\ av}$	$P_{cr\ min}$	HRC_{quen}	HRC_{temp}	
1	595	528	460	59.5	58.5	3.27
3	735	667	595	59.5	58.0	3.37
5	650	625	595	59.5	57.5	3.37
7	695	617	535	59.0	57.0	3.28
14	725	638	585	59.5	57.0	3.34

DISCUSSION

Step quenching with holding at a temperature of 650 °C allows obtaining crack propagation resistance values comparable to standard quenching (in oil) and high tempering at approximately equal values of hardness and total crack and notch depth. This is in good agreement with the study conducted by the authors [13; 16]. They associate the positive effect of step quenching with the formation of microheterogeneities in martensite that have an increased content of carbon, vanadium and molybdenum, which, with subsequent high tempering, are nuclei for the formation of carbides, providing them with high dispersion and uniformity of distribution, thereby increasing the crack propagation resistance [13].

Compared with standard quenching, quenching with a step at 340 °C leads to a significant decrease in hardness, which indicates partial bainitic decomposition. The resistance to crack propagation regardless of the tempering temperature (low, high tempering) is lower than that of the samples after standard quenching. "Bainite brittleness" is probably associated with the formation of upper bainite crystals in the structure, reinforced with cementite-type carbide plates associated with the matrix [19]. It should be noted that there are isolated studies arguing this, for example [14]. Thus, when quenching 5H2SMF die steel, it is necessary to achieve increased stability of supercooled austenite in the intermediate region, thereby preventing bainite precipitation.

A study of the dependence of hardness and crack resistance on the duration (1, 3, 5, 7, and 14 h) of low tempering (200 °C) of 5H2SMF steel showed that with an increase in the holding time from 1 to 14 h, a decrease in hardness is observed. In this case, the maximum crack resistance (P_{cr}) does not correspond to the minimum hardness, which confirms the data on the non-monotonic, saw-tooth nature of the "crack resistance – time" dependence [14]. Attempts to link the non-monotonicity of this dependence with structural transformations are hypothetical, which is understandable if we cite the following quote: "With the development of the foil method and diffraction electron microscopy, it became possible to identify carbide precipitates by microdiffraction. However, it should be recognised that these possibilities have not yet been used, and the available data are contradictory" [20, p. 143]. In this regard, at this stage of the study, experimental data on the effect of the duration of low tempering were accumulated.

CONCLUSIONS

1. Quenching of 5H2SMF die steel with holding at 650 °C allows obtaining values for crack propagation resistance at approximately equal hardness values comparable with standard quenching and high tempering of dies.

2. A significant decrease in hardness during quenching with a step at 340 °C compared to standard quenching regardless of the tempering temperature (low, high tempering) does not allow recommending this mode for industrial application.

3. Heat treatment modes with holding times of 3 and 5 h can be recommended as standard, since they provide the maximum value of crack propagation resistance after standard quenching and low tempering at 200 °C.

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Влияние режимов упрочняющей термической обработки на сопротивление развитию трещины штамповой стали 5Х2СМФ

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Аннотация: В литературных источниках практически отсутствуют данные о влиянии закалки с выдержками в перлитной и бейнитной областях и последующего низкого и высокого отпуска разной продолжительности на сопротивление развитию трещины штамповых сталей, а имеющиеся данные противоречивы. Между тем более «мягкая» закалка с выдержками в промежуточных областях существенно снижает риск образования закалочных трещин и деформацию штампов и штамповой оснастки. В работе образцы из штамповой стали 5Х2СМФ с острым надрезом и искусственно нанесенными трещинами были подвергнуты термической обработке, включающей в себя стандартную закалку 910 °С в масло и закалку от 910 °С со ступенями при 650 и 340 °С с разными видами отпуска (200, 560, 600 и 640 °С) и разной продолжительностью по времени – 1, 3, 5, 7 и 14 ч (для 200 °С) с целью повышения сопротивления развитию трещины. Проведенные исследования позволили установить, что данные по сопротивлению развитию трещины после ступенчатой закалки с выдержкой в области перлитного превращения и последующего высокого отпуска при 560, 600 и 640 °С сопоставимы со стандартной закалкой в масло и высоким отпуском при тех же температурах. Твердость после ступенчатой закалки в области бейнитного превращения (340 °С) во всех случаях значительно ниже при различных режимах отпуска, поэтому сравнить сопротивление развитию трещины со стандартной закалкой не представляется возможным. Установлено оптимальное с точки зрения повышения сопротивления развитию трещины время выдержки (3 и 5 ч) после стандартной закалки от 910 °С в масло и низкого отпуска при 200 °С.

Ключевые слова: штамповая сталь; закалка; отпуск; твердость; сопротивление развитию трещины.

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