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Volumetric Changes and Structural Stresses after Quenching in a Magnetic Field

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Abstract

Introduction. As is well known, the process of steel hardening is accompanied by volumetric changes due to the difference in specific volumes of transforming phases. These volume changes result in structural stresses within the steel. The presence of these stresses in a hardened product negatively affects its resistance to brittle fracture, leading, for example, to decreased safety during operation of steel structures. In this regard, it is essential to improve heat treatment (HT) methods that reduce quenching stresses. One promising method involves applying a permanent magnetic field during phase transformation, which affects the kinetics of transition and resulting transformation products. However, there is a lack of data on volumetric changes during quenching for this method. The aim of this work is to investigate the effects of permanent magnetic fields on volumetric changes and structural stresses during steel hardening.

Materials and Methods. The research was conducted on technical iron and carbon steel 35, 45, U8, U10, U12. Magnetic fields with strengths of 1.4 and 1.6 MA/m were generated in an interpolar gap of the FL-1 electromagnet, designed by Moscow State University. Volumetric changes after conventional and magnetic quenching were quantitatively assessed by measuring the specific volumes using hydrostatic weighing method.

Results. Concentration dependencies of changes in specific volumes of carbon steels during quenching in a magnetic field at temperatures of 800 and 1 000°C were obtained. There were no changes in the volume effect of martensitic transformation in iron and U10 steel when quenching at temperatures higher than 800°C. Different changes in the volume effect were observed in steels with carbon content: from 0 to 1% — reduction in specific volume; from 1.0% to 1.2% — increase in specific volume. Calculation data showed that after quenching without a field, the level of structural stresses increased with an increase in the carbon content in austenite and an increase in the heating temperature for quenching. The influence of the magnetic field was reduced to a decrease in structural stresses in low- and medium-carbon steels and their increase in high-carbon steels. At low tempering temperatures, the level of structural stresses after quenching in a magnetic field was lower for medium-carbon 45 steel, and higher for U12 steel, than after quenching without a field.

Discussion and Conclusion. The data obtained for low- and medium-carbon steels can be explained by the increased degree of martensite decomposition "in statu nascendi" upon cooling in a magnetic field and an increase in the amount of martensite phase in high-carbon iron alloys. The change in the volume effect caused by the increase in the amount of martensite phase under the influence of a magnetic field prevailed over the change in the volume effect caused by its decomposition during the quenching cooling process. The magnitude and sign of the observed effects were determined by the carbon content in the original austenite, and there was a narrow range of concentrations for which magnetic hardening had virtually no effect on the level of structural stresses. The effect of a magnetic field during tempering somewhat slowed down the reduction of residual stresses in the temperature range of martensite decomposition. Structural stresses after heat treatment in a magnetic field, without taking into account the temperature gradient across the cross-section, were mainly determined by the effects obtained during quenching in a magnetic field. The intensification of the phenomena of martensite decomposition caused a decrease, and an increase in the completeness of the martensite transformation, an increase in the level of structural stresses.

Keywords: hardening, steel, volumetric changes, structural stresses, magnetic field, tempering

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Оригинальное эмпирическое исследование

Объёмные изменения и структурные напряжения в стали после закалки в магнитном поле

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Аннотация

Введение. Как известно, закалка стали сопровождается объёмными изменениями, вызванными разностью удельных объёмов превращающихся фаз. Возникающие объёмные изменения приводят к структурным напряжениям в стали. Присутствие напряжений в закаленном изделии сказывается отрицательно на сопротивлении хрупкому разрушению, что обуславливает, например, снижение безопасности при эксплуатации стальных конструкций. В связи с этим важным является совершенствование методов термической обработки (ТО) стали, которые позволяют снизить закалочные напряжения. Наложение постоянного магнитного поля в процессе фазового превращения оказывает влияние на кинетику перехода и образующиеся продукты превращения. Для этого перспективного метода ТО недостаточно данных об объёмных изменениях при закалке. Цель работы — исследование особенностей влияния постоянного магнитного поля на объёмные изменения и структурные напряжения при закалке стали.

Материалы и методы. Исследования проводились на техническом железе и углеродистых сталях 35, 45, У8, У10, У12. Магнитные поля напряженностью 1,4 и 1,6 МА/м создавались в межполюсном зазоре электромагнита ФЛ-1 конструкции МГУ. Количественная оценка объёмных изменений после обычной и магнитной закалки выполнялась путём измерения удельных объёмов методом гидростатического взвешивания.

Результаты исследования. Получены концентрационные зависимости изменения удельных объёмов углеродистых сталей при закалке в магнитном поле от температур 800 и 1 000 °С, на которых отмечалось отсутствие изменений объёмного эффекта мартенситного превращения в техническом железе и стали У10 при закалке от 800 °С, а также наличие разных по знаку изменений объёмного эффекта в сталях с содержанием углерода: от 0 до 1 % — уменьшение удельного объёма, от 1,0 до 1,2 % — увеличение удельного объёма. Расчётные данные показывают, что после закалки без поля уровень структурных напряжений возрастает с увеличением содержания углерода в аустените и повышением температуры нагрева под закалку. Влияние магнитного поля сводится к уменьшению структурных напряжений в низко- и среднеуглеродистых сталях и к их увеличению — в высокоуглеродистых. При низких температурах отпуска уровень структурных напряжений после закалки в магнитном поле для среднеуглеродистой стали 45 ниже, а для стали У12 — выше, чем после закалки без поля.

Обсуждение и заключение. Полученные данные для низко- и среднеуглеродистых сталей объясняются большей степенью распада мартенсита in statu nascendi при охлаждении в магнитном поле и увеличением количества мартенситной фазы в высокоуглеродистых сплавах железа. Изменение объёмного эффекта, вызванное приростом под действием магнитного поля количества мартенситной фазы, превалирует над изменением объёмного эффекта, обусловленного ее распадом в процессе закалочного охлаждения. Величина и знак наблюдаемых эффектов определяются содержанием углерода в исходном аустените, причем существует узкий диапазон концентраций, для которых магнитная закалка не оказывает практически никакого воздействия на уровень структурных напряжений. Действие магнитного поля во время отпуска несколько замедляет снижение остаточных напряжений в температурном интервале распада мартенсита. Структурные напряжения после термической обработки в магнитном поле без учёта температурного градиента по сечению в основном определяются эффектами, полученными при закалке в магнитном поле. Усиление явлений распада мартенсита вызывает снижение, а увеличение полноты мартенситного превращения — повышение уровня структурных напряжений.

Ключевые слова: закалка, сталь, объёмные изменения, структурные напряжения, магнитное поле, отпуск

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Introduction. It is known that steel hardening is accompanied by volumetric changes [1] caused by the difference in specific volumes of converting phases. The resulting volumetric changes [2] lead to structural stresses in steel [3]. The presence of stresses in a hardened product [4] has a negative effect on the resistance to brittle fracture, which, for example, leads to a decrease in safety during operation of steel structures [5].

The application of a permanent magnetic field during phase transformation affects the transition kinetics and the resulting transformation products. In [6, 7], the results of studies of changes in the fine structure and phase composition of steels during quenching in a magnetic field are presented. It has been shown that when exposed to a magnetic field, multiplicative nucleation of martensite crystals occurs and the rate of transformation increases, as well as the temperature of $M_\text{н}$ to $M_\text{д}$ increases with the formation of stress martensite in the range of superplasticity of the transformation [8, 9]. This leads to an increase in the volume fraction of ϰ-martensite due to the early activation of the tempering stage of the freshly formed α-phase, and a decrease in the volume fraction of $A_\text{ост}$. in tool steels, significant thinning in the multiplet profile of the X-ray reflection {211}. The combination of these circumstances leads to changes in phase composition of steels, as well as in structure and properties of transformation products after quenching in a magnetic field.

The development of heat treatment methods that reduce quenching stresses is relevant. The above data on a promising maintenance technology involving an external magnetic field indicate that structural changes occurring under the influence of a magnetic field during quenching can affect the bulk and stress state of steel. However, a detailed research of the effect of the magnetic field on changes in the stress state of hardened steels has not been conducted before. Therefore, the aim of this study is to investigate the volumetric changes and structural stresses that occur due to the application of a permanent magnetic field during the hardening process of steel.

Materials and Methods. The research was conducted on ingot iron and 35, 45, U8, U10, U12 carbon steels. Magnetic fields with strengths $H = 1.4$ and 1.6 MA/m were created in the interpolar gap of an FL-1 electromagnet designed by Moscow State University.

Volumetric changes after conventional quenching and with the application of a magnetic field were quantified by measuring the specific volume by hydrostatic weighing. At the first stage, the samples were weighed in air ($P_\text{В}$). Next, the samples, suspended on a thin nylon thread 8Ø ÷ $18_\text{µm}$ were weighed in distilled water ($P_\text{Ж}$). The value of the specific volume, taking into account the density of distilled water $\delta_\text{Ж}$ and air $\delta_\text{В}$, was determined by the following expression:

$$\upsilon_0 = \frac{P_\text{В} - P_\text{Ж}}{P_\text{В}\left(\delta_\text{Ж} - \delta_\text{В}\right)} + \frac{1}{\delta_\text{В}}. \quad (1)$$

Results. The graph shown in Figure 1 demonstrates the effect of the magnetic field on volumetric changes during martensitic transformation in carbon steels, while the value of the specific volume occurring during conventional quenching was assumed to be zero. It can be noted that the sign of the change in specific volume and its magnitude were correlated with the temperature of heating for quenching and the carbon content in the steel.

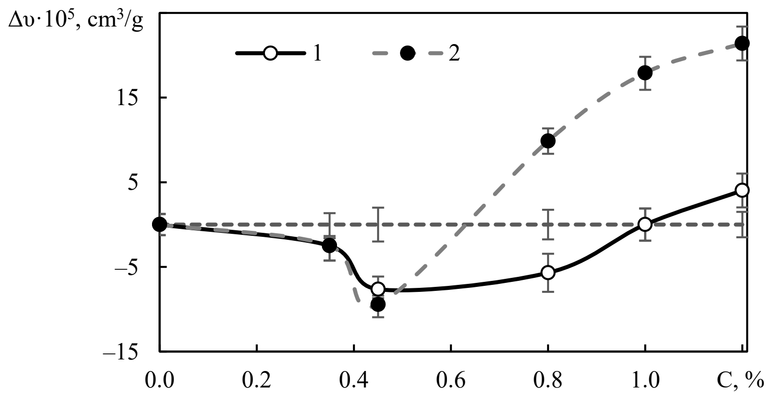

Fig. 1. Relative changes in specific volumes of steels during quenching in an external magnetic field $H = 1.6$ MA/m: 1 — from 800°C; 2 — from 1,000°C

In Figure 1, which shows the dependence of the change in specific volume on the carbon content, the following distinctive features can be observed. First, there is no volumetric conversion effect in pure iron and U10 steel when quenched at a temperature higher than 800°C. Additionally, there were differences in the sign in the volumetric effects change in steels with a carbon content of 0 ÷ 1.0 and 1.0 ÷ 1.2%.When quenching with a magnetic field, there was a decrease in specific volume for steels with 0 ÷ 1.0 % C and an increase for steels with 1.0 ÷ 1.2% C. The largest changes in specific volume occurred at 0.5 and 1.2% carbon. As the quenching temperature increased, the magnitude of the field effect changed and the point with no volume change shifted to lower carbon steel

The occurrence of structural stresses in the alloy was facilitated by volumetric changes during phase transformation, as well as their heterogeneous distribution across micro-volumes [10, 11]. Structural stresses could be calculated using the calculation method presented in [12], which made it possible to determine tangential, axial, and radial stresses in a fully cylinder, assuming that there was no temperature gradient in the analyzed section. The impact of the magnetic field on structural stresses during quenching could be estimated using an expression for calculating the tangential component of stresses on the surface:

$$\sigma_\tau = -\frac{E \cdot l}{2(1-\mu)}, \tag{2}$$

where l — relative value of the structural deformation at the transformation stage; E — modulus of elasticity; μ — Poisson's ratio.

When estimating l, volumetric characteristics of the phases and measurement data of specific volumes of samples of such a small size were used, that the temperature difference between the core and the surface could be ignored. The data in Table 1 show that for the case of conventional quenching, structural stresses increased with the carbon concentration in the initial phase and with the quenching temperature.

Table 1

Structural Stresses (σ_τ) under Various Quenching Conditions

Steel	σ_τ, MPa, at the quenching temperature, °C*		Steel	σ_τ, MPa, at the quenching temperature, °C*	
	800	1,000		800	1,000
45	–600.9 / –549.6	–621.2 / –564.5	U10	–795.4 / –795.4	–923.2 / –1028.7
U8	–774.9 / –766.6	–903.8 / –939.4	U12	–798,6 / –819,7	–888.3 / –1007.0

**Numerator — quenching without a magnetic field; denominator — in H = 1.6 MA/m.*

Table 2 provides the calculation results of the structural stresses caused by transformations during hourly tempering of carbon steels hardened at a temperature higher than 1,000°C.

Table 2

Structural Stresses after Quenching and Tempering

Steel	Magnetic field strength,* MA/m	σ_τ, MPa, at the tempering temperature, ºC (taking into account the austenite yield strength)					
		20	100	150	200	250	300
45	0/0	–421.1	–254.1	–205.3	–163.7	–140.8	–122.2
	0/1.4	–421.2	–273.0	–215.4	–162.9	–140.7	–122.2
	1.6/0	–364.5	–226.1	–196.7	–164.8	–141.1	–122.1
	1.6/1.4	–364.5	–234.4	–200.4	–165.4	–141.7	–122.1
U12	0/0	–688.3	–527.8	–490.7	–536.4	–527.0	–484.2
	0/1.4	–688.3	–584.6	–536.5	–573.7	–531.4	–484.2
	1.6/0	–807.0	–691.7	–634.6	–627.8	–530.7	–484.1
	1.6/1.4	–807.0	–741.6	–670.1	–671.3	–532.7	–484.1

** Numerator — for quenching, denominator — for tempering.*

Discussion and Conclusion. The effects observed in Figure 1 for steels with low and medium carbon content are due to tempering processes occurring directly during quenching cooling in a magnetic field. For steels with high carbon content, the increase in volume fraction of the α-phase is responsible for these effects. An analysis of theoretical calculations [1] shows that for steel 45, after quenching in a magnetic field, a change of $\Delta\upsilon = -9 \cdot 10^{-5}$ cm^3/g is caused by a decrease of 0.04 ÷ 0.05% C in martensite. The observed change in $\Delta\upsilon = 22 \cdot 10^{-5}$ cm^3/g for steel with a carbon content of 1.2% is due to an increase in the volume fraction of the α-phase by 4–5%, assuming that the carbon content in martensite does not change during quenching in a magnetic field compared to conventional quenching.

The comparison of the graph data in Figure 1 with the results of the study on the fine structure of conventional and magnetic quenched martensite [6, 7] allows us to conclude that the change in the volumetric effect caused by an increase in the martensite phase under the influence of a magnetic field prevails over the change in the volumetric effect caused by its decay during quenching cooling.

The effect of the field is manifested in a decrease in structural stresses in steels with low and medium carbon content and their increase in steels with high carbon concentration (see data in Table 1). For example, after quenching 0.45% and 1.2% C steels in a magnetic field with a temperature higher than 1,000°C, the level of structural stresses in the first case decreases by 10%, and in the second case increases by 13%. Comparing the obtained results with the data of X-ray diffraction studies [6, 7], it can be noted that the sign and magnitude of the effects are determined by the concentration of carbon in the initial γ-phase. It is characteristic that for certain concentrations, quenching in a magnetic field has a slight effect on the values of structural stress. These effects of the magnetic field can be explained by the strengthening of tempering processes during the formation of martensite during quenching for steels with low and medium carbon content, and by increasing the volume fraction of martensite for steels with a high carbon content.

The formation of residual stresses during the quenching of steel [13, 14] begins, as is known, at $T_{\text{упр}}$ — temperature of the transition of the material from a plastic state to an elastic one. Therefore, the structural stresses that occur during quenching [15, 16] are composed of stresses caused by a change in the specific volume of the alloy during cooling from a temperature of $T_{\text{упр}}$ to $M_{\text{н}}$. The calculation of the latter by formula (2) shows that when the alloy is cooled to $M_{\text{н}}$ temperature, tensile stresses occur on the surface of a continuous cylinder that exceed the yield strength of austenite (200 MPa) for all the alloys studied. In this regard, after quenching, the stresses on the surface of the solid cylinder will be less than those shown in Table 1 by the value of the yield strength of austenite.

According to Table 2, it can be seen that at low tempering temperatures, the level of structural stresses after quenching in a magnetic field is lower for medium-carbon steel 45, and higher for U12 steel than after quenching without a field. The effect of the magnetic field during tempering slows down the reduction of residual stresses in the temperature range of martensite decomposition.

Thus, the magnitude of structural stresses after heat treatment in a magnetic field in the absence of a temperature gradient across the cross-section is largely determined by the effects obtained during quenching in a magnetic field. An increase in the phenomena of martensite decomposition causes a decrease, and an increase in the completeness of the martensite transformation causes an increase in the level of structural stresses.

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***Claimed Contributorship*:**

VN Pustovoit: concept development, academic advising, methodology development, administrative management of the research project, provision of resources, writing a draft of the manuscript.

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В.Н. Пустовойт: разработка концепции, научное руководство, разработка методологии, административное руководство исследовательским проектом, предоставление ресурсов, написание черновика рукописи.

Ю.В. Долгачев: проведение исследования, формальный анализ, валидация результатов, визуализация, рецензирование и редактирование рукописи.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

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