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Original Empirical Research

Formation of Residual Stress Diagram after Quenching in a Magnetic Field

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Abstract

Introduction. After hardening, a product has residual stresses: structural and thermal. The magnitude of the total stresses in the finished part determines its crack resistance under the influence of operational loads. Quenching in a constant magnetic field affects the process of martensite nucleation, and the kinetics of martensite transformation, as well as the processes of martensite decomposition. However, there is currently no data available on how these changes in structure affect the stress diagram in a heat-treated product. The aim of this study was to investigate the influence of a constant magnetic field during hardening of iron-carbon alloys on the stress distribution across the cross-sectional area of parts.

Materials and Methods. The studies were conducted on samples of technical iron, steel 45, and ferritic malleable cast iron. Cylindrical samples with a diameter of 16 mm and ring samples with an outer diameter of 20 and 55 mm were used. The samples were heated in an electric furnace or an induction heating lamp generator LZ-13, and quenched in water or mineral oil. A constant magnetic field with strength of 768 to 1600 kA/m during hardening was created in the bore of a FL-1 electromagnet. Residual stresses were determined using the original method developed by V.A. Blinovskii based on measuring bending deformations in hollow bodies of revolution.

Results. The change in temperature on the surface, in the core, and the temperature difference across the cross-section of a cylindrical sample during cooling in water with and without a magnetic field was obtained. The distribution of stresses over the cross-section after quenching with and without a field for industrial iron in still water was studied. The stress distribution over the cross-section was studied after quenching in a field and without a field in calm water, as well as during spray cooling of steel 45 and ferritic ductile cast iron at different rates.

Discussion and Conclusion. The obtained calculated and experimental data allowed us to evaluate possible changes in the residual stress diagrams under the influence of a magnetic field after quenching with volumetric and surface heating. A study of the kinetics of cooling in water under the influence of a magnetic field showed that the temperature difference across the cross-section remained practically unchanged, but there was a decrease in the cooling capacity of the water, which contributed to a reduction in the level of thermal stress. Hardening in a magnetic field led to a reduction of residual stresses in iron-carbon alloys. The change in the distribution of total residual stresses during magnetic tempering was due to a change in their structural component. The magnetic field influenced the distribution of structural, thermal and total residual stresses. The reason for the observed effects was the change in the structural state of steel and cast iron and the cooling ability of water-based quenching liquids under the influence of a magnetic field. The reduction of the level of residual stresses during heat treatment in a magnetic field reduced the likelihood of brittle fracture and cracking, led to a decrease in deformation and warping of hardened steels, and created favorable conditions for the operation of parts under conditions of alternating loads and abrasive friction.

Keywords: hardening, steel, cast iron, residual stresses, magnetic field, structural stresses, thermal stresses

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Оригинальное эмпирическое исследование

Формирование эпюры остаточных напряжений после закалки в магнитном поле

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Аннотация
Введение. После закалки в изделии имеются остаточные напряжения: структурные и тепловые. Величина суммарных напряжений в готовой детали определяет её трещиностойкость под действием эксплуатационных нагрузок. Закалка в постоянном магнитном поле оказывает влияние на процесс зарождения мартенсита, кинетику мартенситного превращения, а также процессы распада мартенсита. В настоящее время отсутствуют данные о том, как указанные изменения в структуре влияют на эпюру напряжений в термически обработанном изделии. Цель работы — исследование влияния постоянного магнитного поля при закалке железоуглеродистых сплавов на распределение напряжений по сечению деталей.
Материалы и методы. Исследования проводили на образцах технического железа, стали 45 и ферритного ковкого чугуна. Применялись цилиндрические образцы диаметром 16 мм и кольцевые образцы с наружным диаметром 20 и 55 мм. Образцы нагревали в электропечи или индукционным нагревом токами высокой частоты от лампового генератора ЛЗ-13. Закалку проводили в воде или минеральном масле. Постоянное магнитное поле напряжённостью от 768 до 1600 кА/м при закалке создавалось в зазоре электромагнита ФЛ-1. Определение остаточных напряжений осуществлялось по оригинальной методике В.А. Блиновского, основанной на измерении деформации изгиба в полых телах вращения.
Результаты исследования. Получено изменение температуры на поверхности, в сердцевине и перепад температур по сечению цилиндрического образца при охлаждении в воде без поля и в магнитном поле. Изучено распределение напряжений по сечению после закалки в поле и без поля технического железа в спокойной воде. Исследовано распределение напряжений по сечению после закалки в поле и без поля в спокойной воде, а также при спреерном охлаждении с различной скоростью стали 45 и ферритного ковкого чугуна.
Обсуждение и заключение. Полученные расчетные и экспериментальные данные позволили оценить возможные изменения под действием магнитного поля эпюр остаточных напряжений после завалки с объемным и поверхностным нагревом. Исследование кинетики охлаждения в воде под действием магнитного поля показало, что перепад температуры по сечению оставался практически неизменным, но наблюдалось снижение охлаждающей способности воды, что способствовало снижению уровня тепловых напряжений. Закалка в магнитном поле способствовала снижению остаточных напряжений в железоуглеродистых сплавах. Изменение распределения суммарных остаточных напряжений при магнитном отпуске обусловлено изменением их структурной составляющей. Магнитное поле оказывает влияние на распределение структурных, тепловых и суммарных остаточных напряжений. Причиной наблюдаемых эффектов является изменение под действием магнитного поля структурного состояния стали и чугуна и охлаждающей способности закалочных жидкостей на водной основе. Снижение уровня остаточных напряжений при термической обработке в магнитном поле уменьшает вероятность хрупкого разрушения и трещинообразования, приводит к снижению деформаций и коробления закаленных сталей, создает благоприятные условия для работы деталей в условиях знакопеременных нагрузок и абразивного трения.

Ключевые слова: закалка, сталь, чугун, остаточные напряжения, магнитное поле, структурные напряжения, тепловые напряжения

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Introduction. Residual stresses after quenching are usually divided into two main categories: structural [1, 2] and thermal [3, 4]. Thermal stresses arise from the simultaneous influence of two factors: changes in the specific volume of the metal with temperature and the presence of a temperature gradient in the product undergoing heat treatment. Structural stresses are caused by dilation effects from phase transitions, especially when phase transformations occur inhomogeneously throughout the volume of a part. Thus, the resulting stresses in a processed product are formed through the addition of structural and thermal stress. It is known [5, 6], that the main factor determining the magnitude of stress after quenching is the moment when the sign of thermal stresses changes relative to the moment when structural stresses occur. The appearance of structural stresses prior to changing the sign of thermal stresses leads to an increase in the resulting stresses in the product. Accordingly, the occurrence of structural stresses before the sign of thermal stresses changes lowers the total stresses. The magnitude of the total stresses in a finished part determines the reliability of machine-building products during operation [7, 8]. The influence of a constant magnetic field during quenching of steels and cast irons is manifested through the process of martensite nucleation, changes in the kinetics of martensite transformation, as well as changes in tempering processes occurring directly during quench cooling. It is currently unknown how a magnetic field affects the residual stress in a heat-treated product. The aim of this work is to investigate the influence of a constant magnetic field during iron-carbon alloy quenching on the stress distribution over the section of parts.

Materials and Methods. In this work, samples of technical iron, steel 45, and ferritic ductile iron were studied. Cylindrical samples with a diameter of 16 mm and annular samples with outer diameters of 20 and 55 mm were used. The samples were heated in an electric furnace or by induction heating using high-frequency currents from a lamp generator LZ-13. During quenching, a constant magnetic field with strengths ranging from 768 to 1,600 kA/m was created in the FL-1 bore of the electromagnet.

The determination of residual stresses was carried out according to the original methodology developed by V.A. Blinovskii [9]. This technique is based on measuring bending deformation in hollow rotational bodies. It provided for cutting out an annular sector from a sample and measuring the resulting diameter changes. The resulting deformation curve served as the initial input for calculating residual stresses using a computer.

Research Results and Discussion. When quenching steel, the temperature gradient, which caused inhomogeneous changes in specific volume over the cross-section of the part, influenced the formation of a residual stress diagram. With a significant temperature difference between the surface and the core at the time of martensitic transformation (such as during through-quenching with water cooling after heating in a furnace), compressive tangential and axial stresses developed on the surface of a solid cylinder. Conversely, quenching in oil, where the temperature difference between core and surface was minimal at the time of martensitic transformation, resulted in tensile stresses on the surface. In this case, the stress diagram developed in the following manner. Rapid cooling of the surface caused volume reduction, but a higher temperature persisted within, counteracting volume decrease and leading to tensile stress in the outer layer. At the same time, plastic deformation of the outer layers was possible up to temperatures $T_{упр}$(~500–550°C). With further cooling, plasticity decreased, σ_T increased and only elastic deformations remained possible, which led to an increase in tensile stresses. Their growth continued until the cooling of inner layers, which shifted the maxima of tensile stresses to the center and slightly reduced surface tensile stresses. With a sufficient heating depth (almost more than 2 mm), the reduction in the volume of central layers led not only to the complete elimination of initial tensile stresses, but also to the appearance of compressive stresses on the surface, which persisted after the end of cooling.

When surface layers were cooled to point $M_н$, the quenching process led to an increase in volume. At the same time, inner layers that did not undergo hardening prevented this increase, which formed tensile stresses in the inner layers and compressions in the surface layers. As the quenching front moved away from the surface, the compressive stresses decreased and their maximum shifted to the center. As a result, after quenching, the stresses on the surface might have a different sign (although they might remain unchanged). The magnitude of compressive stresses in the surface layer increased with decreasing depth of the hardened layer.

Figure 1 shows the results of the study on the kinetics of cooling in water of a 16 mm diameter sample made of armco-iron. As can be seen, when a magnetic field was applied, the temperature drop across the cross-section of the samples remained almost unchanged, however, time dependence Δt shifted towards longer cooling durations. This was due to a decrease in the cooling capacity of water in a magnetic field [10, 11] and contributed to more intense stress relaxation by plastic deformation, as a result of which a decrease in the level of thermal stresses was observed (Fig. 2). Consequently, a magnetic field during quenching affected the formation of both structural and thermal components of residual stresses.

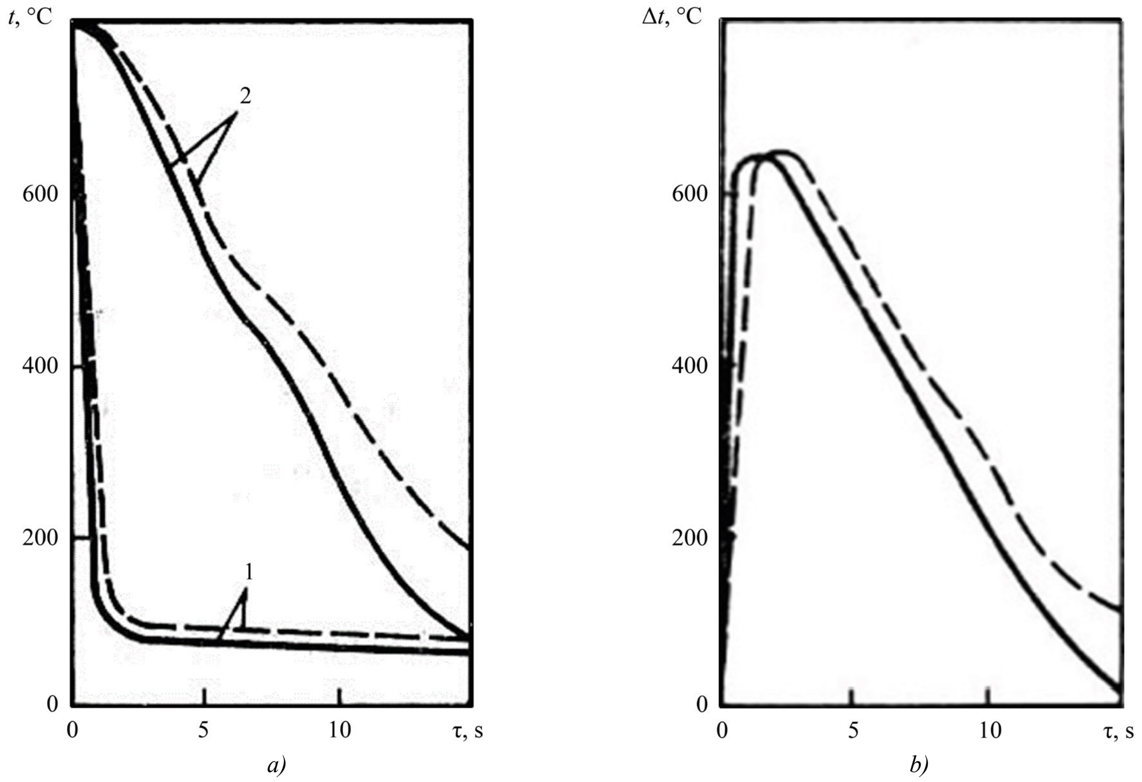


Fig. 1. Temperature changes in a cylindrical sample during cooling in water:
solid line — without a field; dashed line — in a magnetic field with a strength of 1.6 MA/m;
a — on surface 1 and in core 2; *b* — difference in cross section

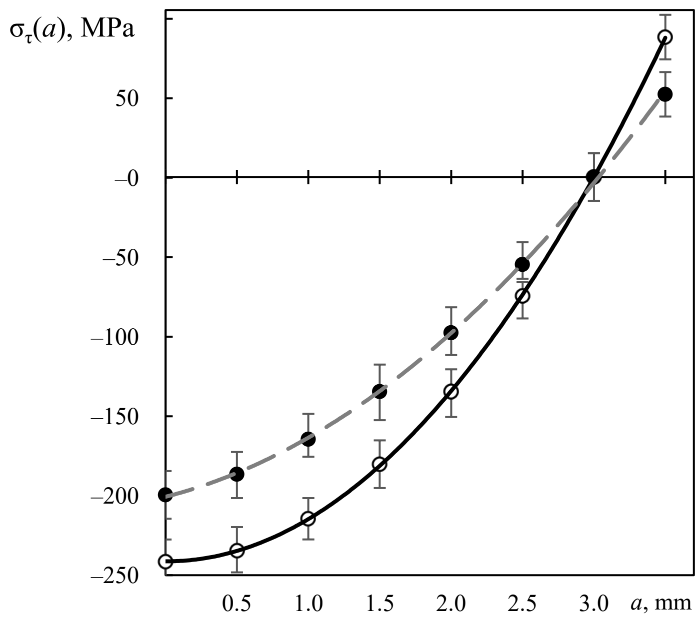
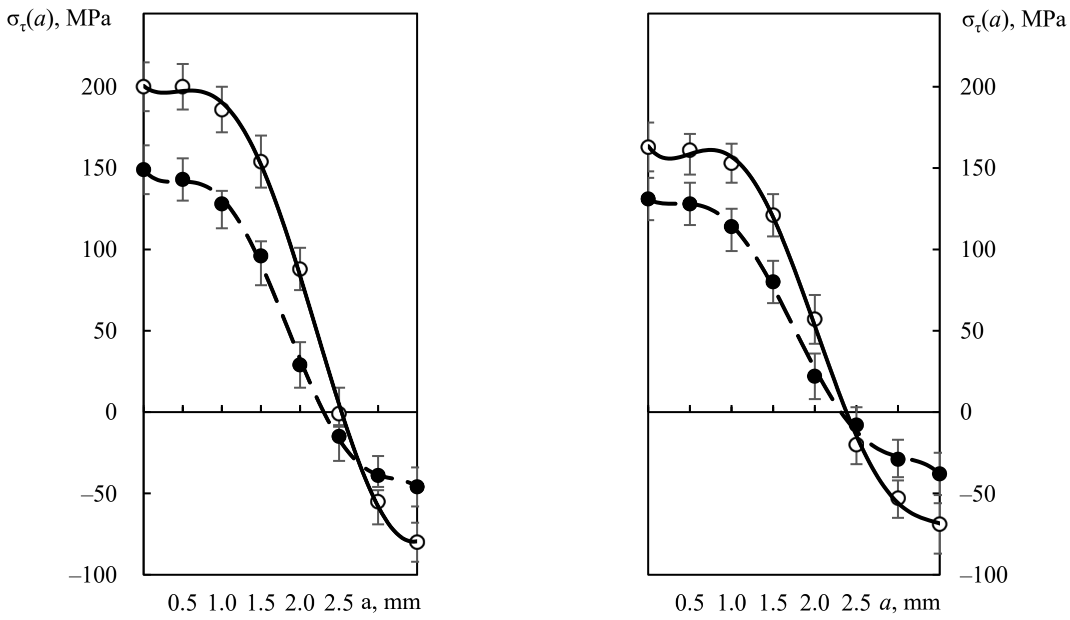


Fig. 2. Stress distribution over the cross section after quenching of technical iron from 800°C in calm water:
solid line — without a field; dashed line — in a magnetic field with a strength of 1.4 MA/m

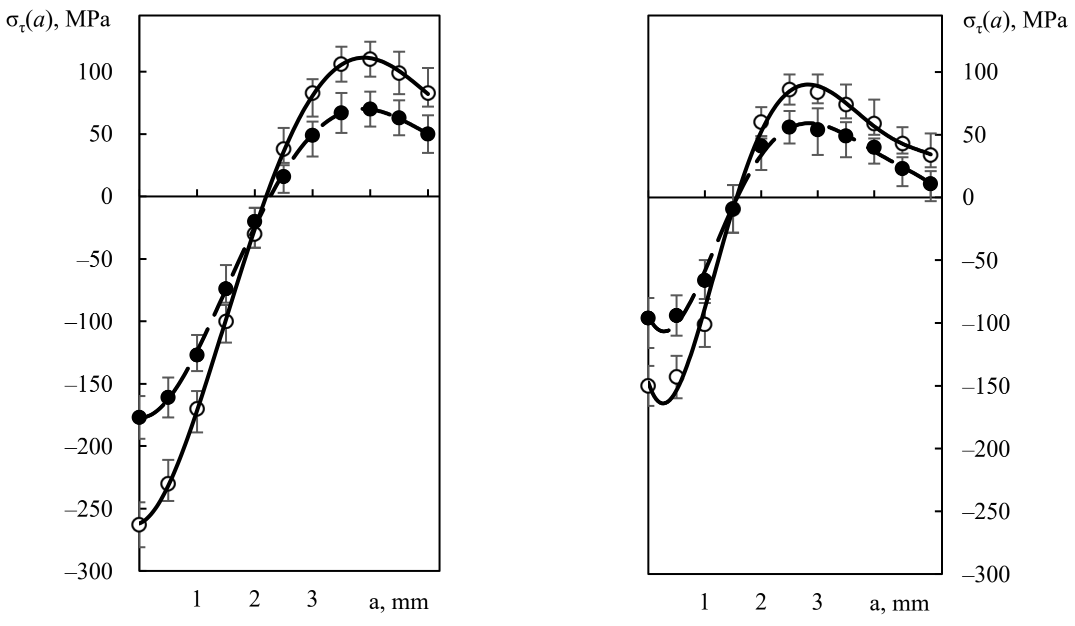
To assess the effect of the magnetic field on the distribution of total residual stresses in hardened and tempered alloys, the experiments were conducted, the results of which are shown in Figure 3. After the usual hardening of annular samples with an outer diameter of 20 mm, tensile stresses were observed on the surface. This was explained by the small temperature difference between the periphery and the center during martensitic transformation. Therefore, their structural component had a predominant effect on the distribution of total residual stresses. Quenching in a magnetic field helped to reduce residual stresses in alloys with both negative (steel 45) and positive (ferritic ductile iron) changes in the volumetric effect of martensitic transformation. This indicated that the main reason for the reduction of residual stresses was their intense relaxation under the action of a magnetic field. An increase in the degree of martensite decay under the influence of a magnetic field [12] caused an increase in this effect.



a) *b)*

Fig. 3. Stress distribution over the cross section after quenching from 1000°C in calm water, solid line — without a field; dashed line — in a magnetic field with a strength of 1.4 MA/m; *a* — steel 45; *b* — ferritic ductile iron

Similar patterns were observed during spray cooling with water of annular samples with a diameter of 55 mm (Fig. 4). The difference was in the fact that exposure to a magnetic field caused a decrease in surface compressive stresses due to the prevailing influence of the thermal component of residual stresses on the total stress diagram.



a) *b)*

Fig. 4. Stress distribution after quenching from 1000°C with spray cooling with water υ = 2 m/s: solid line — without a field; dashed line — in a magnetic field with a strength of 768 kA/m; *a* — steel 45; *b* — ferritic ductile iron

An increase in the velocity of water flow through the sprayer to υ = 10 m/s led to an increase in the magnitude of surface compressive stresses during conventional quenching. At such a flow rate, the cooling capacity and the degree of "quenching" stress relaxation under the influence of a magnetic field changed slightly. Therefore, the observed changes were mainly due to a structural factor: an increase in the degree of breakdown of martensite in steel 45 and an increase in the amount of martensite in ductile iron.

Table 1

The effect of cooling in a magnetic field after heating in a furnace on the level of residual stresses

Parameters	Carbon-free alloys		Medium-carbon alloys		High-carbon alloys	
	Cooling medium					
	Water	Oil	Water	Oil	Water	Oil
Stresses on the surface of a solid cylinder after conventional cooling	Compressive	Compressive, but less than when cooled in water	Compressive	Tensile	Compressive	Tensile
Change in stresses on the surface of a solid cylinder after cooling in a magnetic field as a result of: reducing the cooling capacity of quenching liquids	Decrease in compression	–	Decrease in compression	–	Decrease in compression	–
increase in the amount of martensite	–	–	–	–	Increase in compression	Increase in tension
increase in the decay processes of martensite ("in statu nascendi")	–	–	Decrease in compression	Decrease in tension	Decrease in compression	Decrease in tension

Table 2

The effect of cooling in a magnetic field after induction (surface) heating on the level of residual stresses

Parameters	Carbon-free alloys		Medium-carbon alloys		High-carbon alloys	
	Depth of the hardened layer					
	low	high	low	high	low	high
Stresses on the surface of a solid cylinder after conventional cooling	Tensile	Compressive	Compressive		Compressive	
Change in stresses on the surface of a solid cylinder after cooling in a magnetic field as a result of: reducing the cooling capacity of quenching liquids	Decrease in tension	Decrease in compression	Decrease in compression		Decrease in compression	
increase in the amount of martensite	–	–	–		Increase in compression	
increase in the decay processes of martensite («in statu nascendi»)	–	–	Decrease in compression		Decrease in compression	

Discussion and Conclusion. The calculated and experimental data made it possible to estimate the possible changes in the residual stress diagrams under the influence of a magnetic field after quenching with volumetric (Table 1) and surface heating (Table 2). The change in the distribution of total residual stresses during magnetic release was due to a change in their structural component.

Thus, the magnetic field affects the distribution of structural (during quenching and tempering), thermal (during quenching) and total residual stresses. The reason for the observed effects is the change in the structural state of steel and cast iron and the cooling capacity of water-based quenching liquids under the influence of a magnetic field. An increase in the phenomena of martensite decay causes a decrease, and an increase in the completeness of martensite transformation causes an increase in the level of structural stresses. A decrease in the cooling capacity of water-based quenching liquids leads to a decrease in residual stresses as a result of intensive relaxation by plastic deformation. The enhancement of relaxation processes under the influence of a magnetic field in most cases is the main factor in changing the residual stress diagram. In turn, reducing the level of residual stresses during heat treatment in a magnetic field can reduce the likelihood of brittle fracture and cracking, as well as deformations and warping in hardened steels. This creates favorable conditions for the performance of parts under alternating loads and abrasive friction.

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Claimed Contributorship:

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YuV Dolgachev: obtaining experimental data, calculations, analysis of the research results, preparation of the text, formulation of the conclusions.

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