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Elimination of Distortion during Strengthening Heat Treatment of Small Rod Products

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Abstract

Introduction. Rod-shaped products, such as various needles, axles, pins, shafts, studs, plungers, etc., are in high demand in modern industry. In production of small long products, distortion of their shapes due to the action of internal stresses caused by uneven heating, cooling, deformation or phase transformations of the metal, is a pressing issue. Known methods for eliminating warping involve additional mechanical straightening (often manual), which increases labor intensity and product costs while reducing product performance. To avoid this phenomenon, the use of magnetic field heat treatment (MFHT) technology is proposed. This technology facilitates the initiation of stress-induced martensite within the superplastic temperature range of austenite, along with the simultaneous constraint of the rod product along the magnetic flux. Therefore, the objective of the present study is to explore the feasibility of reducing distortion in rod-shaped products by applying a magnetic field during heat treatment. It is proposed to test the capabilities of MFHT technology on machine needles, where the warping criterion is the magnitude of residual deformation, and the key property indicators are hardness and fatigue limit. The study involves testing needles during both serial and experimental processing, including between different process steps.

Materials and Methods. Machine needles made of U10A steel (GOST 1435-99) with diameters of 0.65 mm, 0.75 mm, 1.10 mm and 1.20 mm were studied. Standard processing modes and MFHT processing on a special installation were used. The radial runout value was measured. The fine structure was studied using TEM and X-ray diffractometry. The operational characteristics were assessed by fatigue tests with determination of the fatigue limit.

Results. The data on the distribution of radial runouts and deviation angles of the needle tip after conventional quenching and low tempering, as well as after MFHT and low tempering were obtained. The operational characteristics (fatigue limit) of needles with different warping after standard treatment and after MFHT were estimated. Changes in the parameters of the fine structure of martensite after quenching in a magnetic field were studied. The dispersion of the martensite structure (packet and twinned morphology) after conventional quenching and MFHT was analyzed. Data on the change in hardness along the length of the needle after various treatment modes were presented.

Discussion. Experimental data obtained demonstrate the feasibility of eliminating warping in small rod-shaped components using the MFHT hardening technology. Hardening in a magnetic field involves a kind of internal straightening and constraining of the long axis of the product in a vertical position along the magnetic flux lines.

Conclusion. Experimental evidence demonstrates that the hardening technology involving heat treatment in a magnetic field (MFHT), which relies on steel quenching under a magnetic field, can additionally eliminate radial runout in rod-shaped products. The internal straightening process, which is achieved using a specified MFHT processing scheme, eliminates the need for conventional machining, which reduces performance characteristics.

Keywords: small rod products, needles, tool steel, warping, magnetic field hardening, radial runout

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Устранение короблений при упрочняющей термической обработке мелких стержневых изделий

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Аннотация

Введение. Стержневые изделия, например всевозможные иглы, оси, штифты, валы, шпильки, плунжеры и др., широко востребованы в современной промышленности. В технологическом процессе производства мелких длинномерных изделий существует проблема искажения их форм вследствие действия внутренних напряжений, вызванных неравномерным нагревом, охлаждением, деформацией или фазовыми превращениями металла. Известные способы устранения коробления предполагают дополнительную механическую правку (зачастую ручным способом), что увеличивает трудоёмкость производства и себестоимость продукции, при этом снижаются эксплуатационные характеристики изделий. Чтобы избежать этого явления, предлагается использовать особенности технологии термической обработки в магнитном поле (ТОМП), которые обуславливают возможность зарождения мартенсита напряжения в температурном интервале сверхпластичности аустенита и одновременного заневоливания стержневого изделия вдоль магнитного потока. Таким образом, целью настоящей работы является исследование возможности уменьшения коробления продукции стержневой формы с помощью воздействия магнитным полем при термической обработке.

Возможности технологии ТОМП предлагается апробировать на машинных иглах, в качестве критерия коробления которых выступает величина остаточной деформации, а основными показателями свойств являются твёрдость и предел выносливости. Исследование игл проведено в процессе серийной и экспериментальной технологии обработки, в том числе между различными операциями технологического процесса.

Материалы и методы. Изучались машинные иглы из стали У10А диаметром 0,65, 0,75, 1,10 и 1,20 мм. Применялись стандартные режимы обработки и обработка ТОМП на специальной установке. Измерялась величина радиального биения. Исследовалась тонкая структура с помощью ПЭМ и рентгеновской дифрактометрии. Эксплуатационные характеристики оценивались усталостными испытаниями с определением предела выносливости.

Результаты исследования. Получены данные о распределении радиальных биений и углов отклонения острия игл после обычной закалки и низкого отпуска, а также после ТОМП и низкого отпуска. Дана оценка эксплуатационным характеристикам (пределу выносливости) игл с различным короблением после стандартной обработки и после ТОМП. Представлены изменения параметров тонкой структуры мартенсита после закалки в магнитном поле, анализ дисперсности структуры мартенсита (пакетной и двойниковой морфологии) после обычной закалки и ТОМП. Показаны изменения твердости по длине иглы после различных режимов обработки.

Обсуждение. Результаты проведенных экспериментов свидетельствуют о возможности устранения коробления мелких стержневых деталей при использовании упрочняющей технологии ТОМП. Закалка в магнитном поле сопровождается своеобразной внутренней правкой и заневоливанием длинной оси изделия в вертикальном положении вдоль линий магнитного потока.

Заключение. Опытным путем получены свидетельства того, что упрочняющая технология ТОМП, основанная на закалке стали в магнитном поле, позволяет дополнительно устранять радиальные биения изделий стержневой формы. В процессе внутренней рихтовки, которая реализуется особой схемой обработки ТОМП, исключается необходимость обычной мехобработки, снижающей эксплуатационные характеристики изделия.

Ключевые слова: мелкие стержневые изделия, иглы, инструментальная сталь, коробление, закалка в магнитном поле, радиальные биения

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Introduction. In modern industry, various rod-shaped products with $(\text{length}(L))/(\text{diameter}(D)) > 10$ ratio are in high demand. These include all kinds of needles (sewing, industrial, medical), axles, pins, shafts, studs, plungers, etc. Heat treatment of such products, used to form the required properties of the finished product, is associated with severe warping [1, 2]. This problem is solved through subsequent straightening and alignment operations [3, 4]. However, this approach has its drawbacks. Firstly, such procedures are quite labor-intensive, as they are often performed manually, which increases the cost of production ($\geq 50\%$ of the original cost [5, 6]). Secondly, they can have a negative impact on the product performance properties, reducing its service life [7, 8].

To solve the problem identified, it is proposed to use the features of heat treatment technology in a magnetic field [9]. Under the impact of a magnetic field, stress-induced martensite can nucleate [10], which makes it possible to straighten the internal structure of the product through acting in a state of superplasticity [11, 12] and simultaneously forcing the processed rod along the magnetic field vector. The effect of MFHT (hardening efficiency of $8 \div 12\%$) is comparable in character to that of high-temperature thermomechanical treatment (HTMT) ($19 \div 24\%$) [13, 14], in that both methods simultaneously improve resistance to plastic deformation and brittle fracture. It is known that when using MFHT, the optimal combination of properties is formed by quenching in a magnetic field with tempering without a field [9].

The capabilities of the MFHT technology are proposed to be tested on machine needles, where the warping criterion is the magnitude of residual deformation (radial runouts), and the key property indicators are hardness and fatigue limit. The needles are expected to be studied under serial and experimental processing, including between different process steps.

The objective of this work is to study the possibility of reducing the warping of rod-shaped products by exposing them to a magnetic field during heat treatment.

Materials and Methods. The study utilized products from the Artinsk Mechanical Plant: 100 machine needles (GOST 22249-82) of varying diameters (0.65, 0.75, 1.10, and 1.20 mm) for each mode. The needles were made of U10A steel needle wire (GOST 1435-99). The chemical composition of this wire is listed in Table 1.

Table 1

Chemical Composition of Wire for Making Needles

Batch number	Diameter, mm	C, %	Mn, %	Si, %	S, %	P, %
367	1.90	0.98	0.20	0.18	0.014	0.020
598	1.64	1.01	0.26	0.29	0.015	0.023
1239	2.04	1.01	0.27	0.28	0.013	0.016
471	2.04	1.03	0.27	0.29	0.016	0.021

These products undergo numerous technological processing stages during the manufacturing process, due to their design features. The following main operations can be distinguished: mechanical processing, heat treatment, and finishing operations (chrome plating). After all the shaping operations, the needles undergo heat treatment, retaining their original granular pearlite structure. The standard heat treatment regime involves partial quenching and low tempering. Quenching was performed in heated oil ($\sim 60^\circ\text{C}$). After quenching, the hardness should be $59 \div 63$ HRC. Tempering was performed in oil baths at $200 \div 225^\circ\text{C}$ for 30 minutes. The hardness of the shank after tempering was $53 \div 59$ HRC, and the hardness of the butt was at least 23 HRC.

The MFHT was conducted on the laboratory setup described in [15]. The key feature of the setup is that the needle is heated and held vertically at the top of the furnace by a magnetic field generated by a solenoid. When the needle temperature reaches $\sim 745^\circ\text{C}$, it loses its magnetic properties and falls vertically, simultaneously heating to 780°C in the furnace, into the quenching tank. A magnetic field is applied here, which promotes the intensive formation of martensite and vertical forcing of the product. This is followed by tempering without a magnetic field. As shown in [9], applying a magnetic field during tempering of hypereutectoid steels is inadvisable, as it inhibits the decomposition of the solid solution.

To study the fine structure, UEMV-100K (universal electron microscope) was used for direct transmission of the foil, and DRON-0.5 X-ray (multifunctional X-ray diffractometer) with a FeK α tube.

The degree of warping was assessed through measuring the radial runout using “EC METAM PB-22” (metallographic aggregate microscope of the unified METAM series with an upper stage location) and “Micromed MC-2-Zoom vap.2CR” (stereoscopic microscope) with an Eakins digital eyepiece attachment and an object micrometer.

Hardness measurements were performed using the Rockwell and Vickers standardized techniques on TK-2M and ITBRV-187.5-M hardness testers, respectively.

Transverse bending fatigue tests were conducted with a pulsating load generated by an asynchronous electric motor. The fatigue limit was determined using V.S. Ivanova's method [16].

To process the array of data obtained, the MS Excel statistical functions package was used; histograms, diagrams and graphs were also created in this environment.

Research Results. Standard processing forms the structure of the needles, which determines the following properties: fatigue limit $\sigma_{-1} = 480$ MPa, residual deformation $\Delta l_{\text{oct.}} \approx 0.15$ mm (for a needle with a diameter of $\varnothing 1.20$ mm). The smaller the diameter of the needles, the lower the value of residual deformation after heat treatment; for example, for a diameter of $\varnothing 0.75$ mm, it decreases to $\Delta l_{\text{oct.}} = 0.07 \div 0.08$ mm.

An important operational parameter of the needle is the radial runout (l) of the rod axis relative to the butt axis. Radial runouts [17, 18] arise from internal stresses caused by uneven plastic deformation under machining and temperature distribution during heat treatment operations. Radial runouts are eliminated at various stages of the manufacturing process (reducing, milling, punching, sharpening, grinding, heat treatment, galvanizing, polishing, etc.) through a series of correct operations. Therefore, to produce high-quality products and reduce labor costs, it is necessary to eliminate factors causing radial runouts in the manufacturing process.

The distribution of needle radial runout values (l) and angles (φ) of tip deviation from the vertical axis after standard machining are shown in Figures 1 and 2.

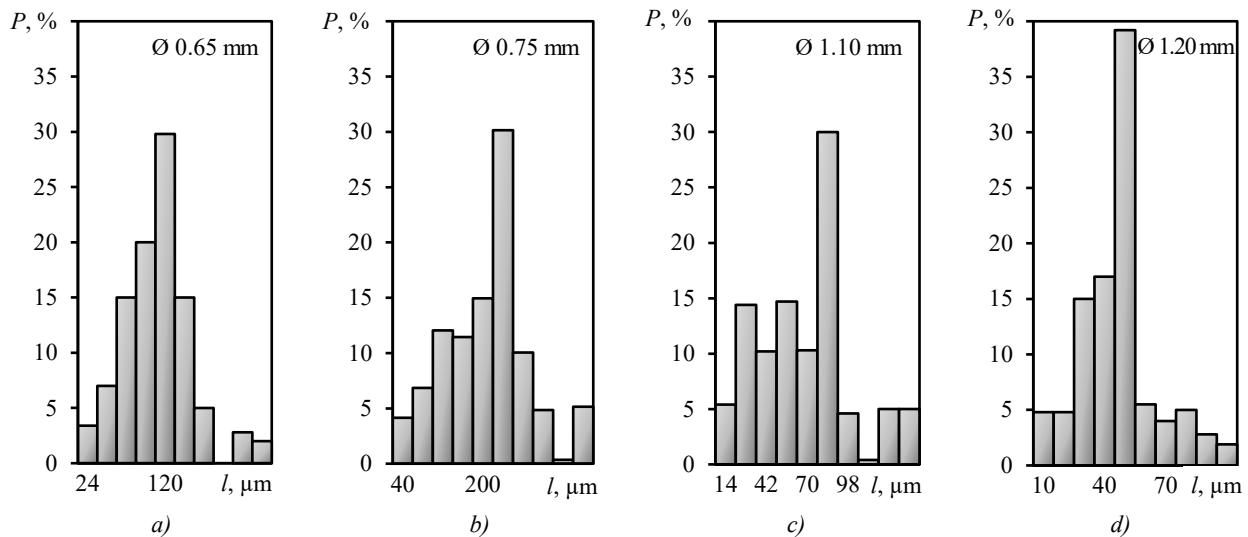
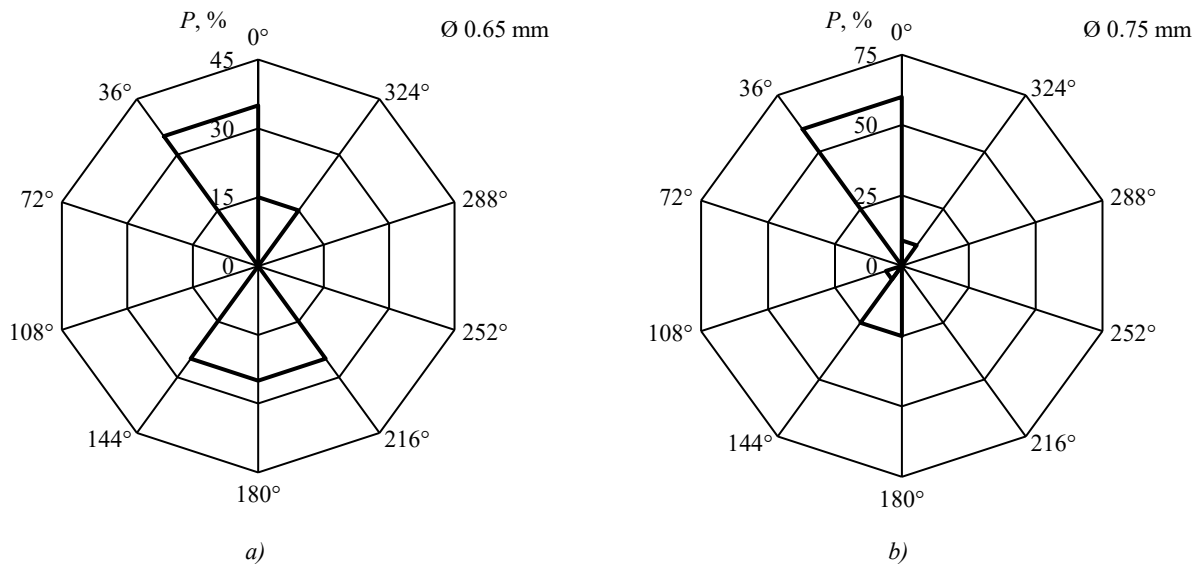


Fig. 1. Distribution of radial runouts (l) of needles of different diameters after hardening:
a — $\varnothing 0.65$ mm; b — $\varnothing 0.75$ mm; c — $\varnothing 1.10$ mm; d — $\varnothing 1.20$ mm



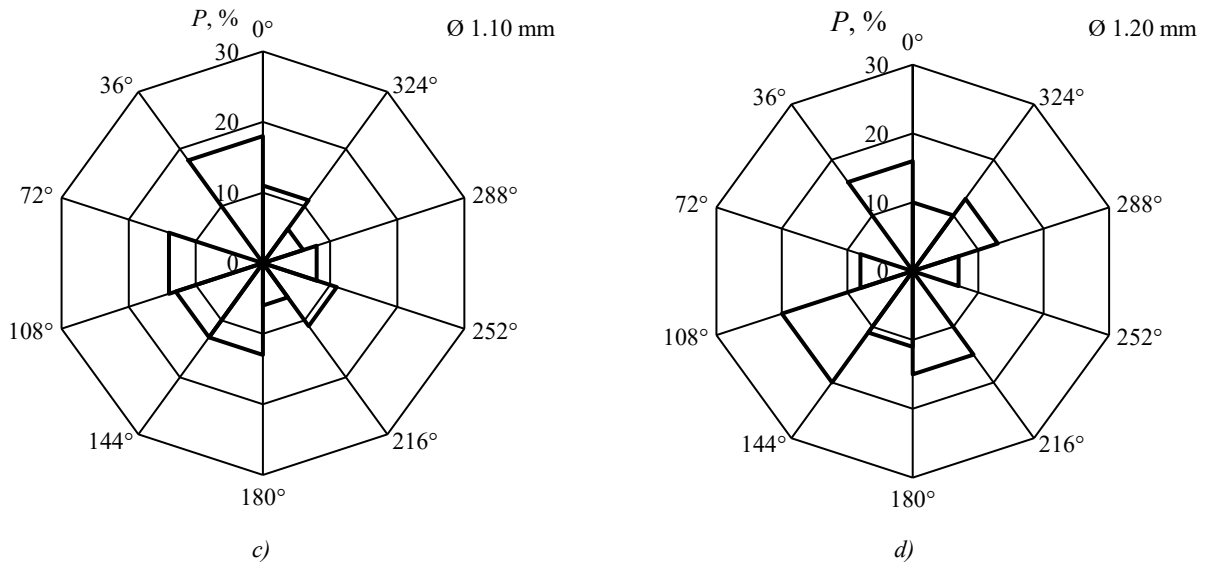


Fig. 2. Distribution of angles (φ) of deviation of tip of needles of different diameters from vertical axis (reference point is milled groove) after hardening:
a — Ø 0.65 mm; b — Ø 0.75 mm; c — Ø 1.10 mm; d — Ø 1.20 mm

After hardening of Ø 0.65 mm diameter products, the range of dispersion values was similar to the results obtained after machining. They amounted to ~0.3 mm, while the technical specifications required $l_0 \leq 0.1$ mm for finished products. Half of the 100 processed needles had an excess of this parameter. A tendency for deviation (φ) of the shank either towards the milled groove (45%) or in the opposite direction (40%), can be noted. This behavior is attributed to the preferential orientation of internal stresses induced by machining operations (both preliminary and finishing). Quenching does not eliminate all of these stresses, and they accumulate with thermal stresses and ultimately result in the observed warping.

A similar pattern was observed for Ø 0.75 mm: 60% of the shanks deviated toward $\varphi = 0^\circ$, while 25% deviated toward $\varphi = 180^\circ$. Warping exceeding the permissible limit for this diameter ($l_0 \leq 0.15$ mm), was found in 65% samples, maximum value of $l=0.4$ mm. Hardening of larger diameter products (Ø 1.10 mm, Ø 1.20 mm) resulted in maximum warping ($l = 0.14$ and 0.10 mm, respectively), satisfying the requirements of the technical specifications ($l_0 \leq 0.15$ mm), and the distribution of the tip deflection angles (φ) was equally probable.

Tempering narrowed the range of maximum warping values l (Fig. 3) by the following values: Ø 0.75 mm — 0.04 mm; Ø 1.10 mm — 0.02 mm. For products of smaller diameters, a twofold increase in the proportion of products meeting technical specifications was observed. For Ø 1.10 mm (Fig. 4), equally probable distribution φ , was characteristic, while for Ø 0.75 mm, it had a preferential direction: 30 % — $\varphi \approx 0^\circ$, 50 % — $\varphi \approx 180^\circ$.

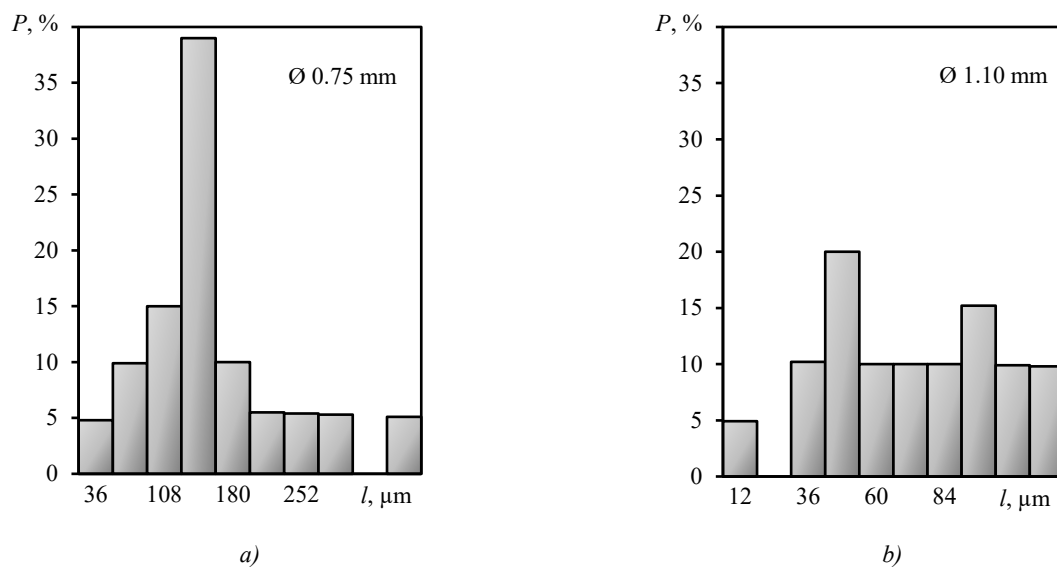


Fig. 3. Distribution of warping value (l) after low tempering:
a — Ø 0.75 mm; b — Ø 1.10 mm

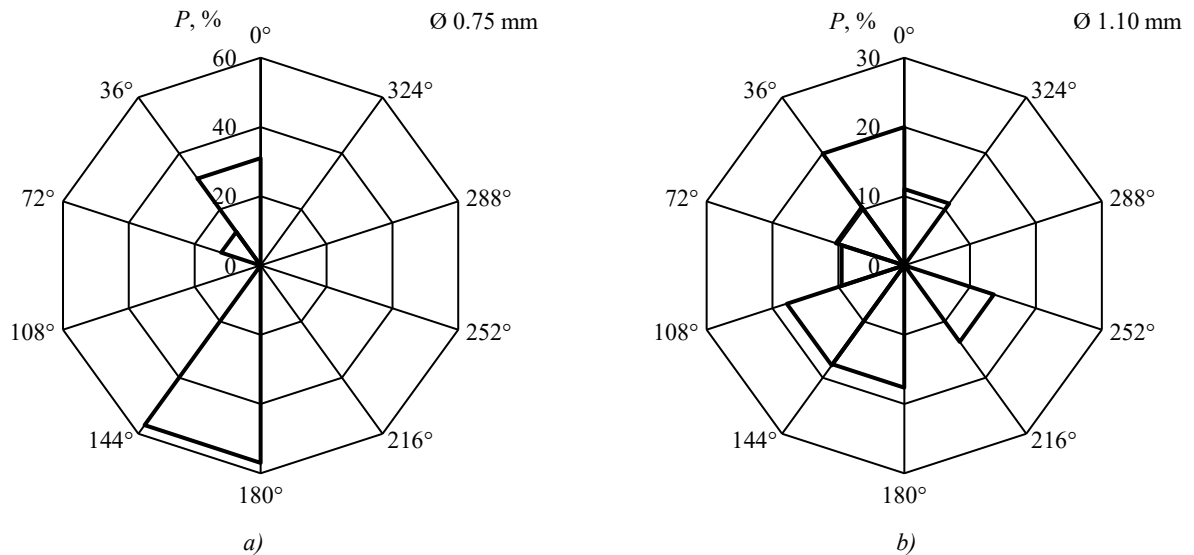


Fig. 4. Distribution of angles (φ) of deviation of tip of needles of different diameters from vertical axis (reference point is milled groove) after tempering:
a — $\varnothing$ 0.75 mm; b — $\varnothing$ 1.10 mm

The conducted studies of products with different levels of warping established that the best performance characteristics (σ_{-1} , $l_{\text{ост.}}$) were shown by products which, during manufacturing, either exhibited no warping after heat treatment or only minimal warping, and consequently were not subjected to straightening operations (Table 2).

Table 2

Performance Characteristics of $\varnothing$ 0.65 mm Diameter Products with Varying Warping

l , μm	$l_{\text{ост.}}$, mm	σ_{-1} , MPa
0–20	0.02–0.08	460–480
0–20 (after alignment)	0.16–0.24	420–440
80–100	0.32–0.36	400–420
180–200	0.34–0.40	370–410

Morphology studies [9, 10] revealed no qualitative difference between the stress-induced cooling martensite obtained under quenching in a magnetic field and after conventional quenching. X-ray structural studies showed that the effect of the magnetic field was reduced mainly to an increase in the volume fraction of V_{α} α -martensite (by 10% when quenched from 1000°C) and a decrease in the tetragonality of α -martensite (Fig. 5).

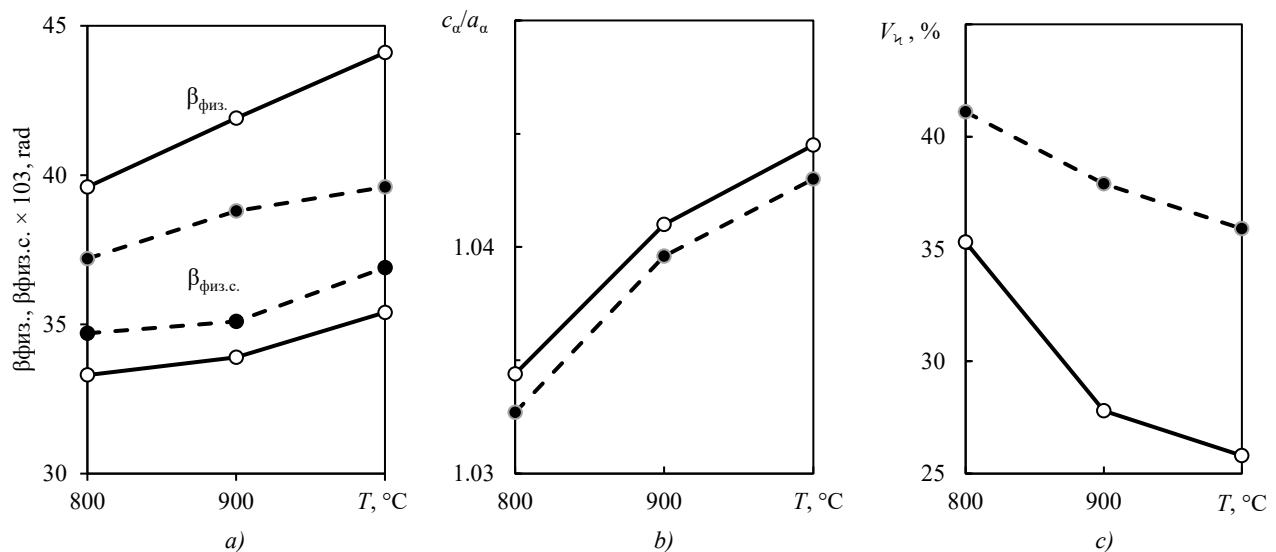


Fig. 5. Results of X-ray structural studies on martensite parameters in U10 steel (solid line — conventional quenching, dashed line — quenching in field $H = 1.2$ MA/m): a — change in physical profile of diffraction lines; b — tetragonality parameter of α - martensite; c — volume fraction of α - martensite

When quenching in a magnetic field, compared to conventional quenching, a consistent broadening of the martensite singlet $\beta_{\text{физ.с.}}$ was observed due to a greater number of crystal structure disturbances. Under the impact of the field, the degree of two-phase decomposition increased, as clearly indicated by the narrowing physical profile of the martensite X-ray diffraction line multiplet $\beta_{\text{физ.}}$.

Metal foil transmission studies showed that the resulting martensite had a mixed morphology (lath+twinned crystals) under all processing conditions. It was established that the high defect density during field quenching was explained by the increased dispersion of the martensitic reaction products. The results of the statistical evaluation of fine structure elements are shown in Figure 6. The effect of the magnetic field is manifested in the refinement of lath martensite (reduction in the number of large packets), more uniform packet sizes, a tendency toward reduced lath thickness within packets, and an increase in the proportion of lath martensite itself (by $12 \pm 4 \%$). The morphological changes are due to the boundary between different martensite types shifting toward regions of higher carbon concentration. These changes are attributed to the explosive kinetics of multiple martensite nucleation: cooling-induced nuclei in the martensite start temperature region, and stress-induced nuclei in the superplasticity region of the martensitic transformation (slightly above M_{H}). Furthermore, the field enhances the role of deformation slip in α -phase nucleation.

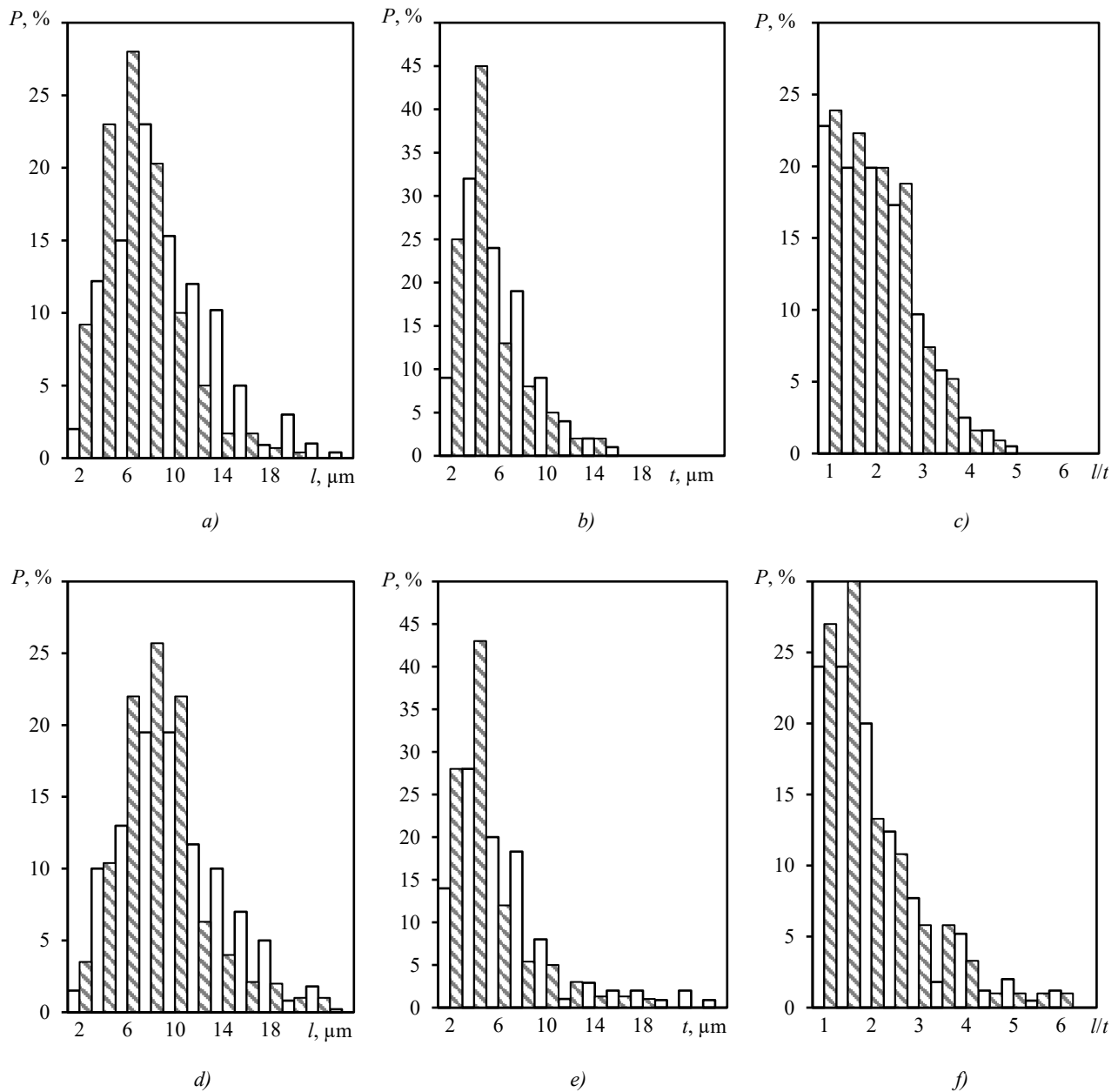


Fig. 6. Distribution of length (l), width (t) and formfactor (l/t) of martensite in U10A steel after conventional quenching (white columns) and quenching in magnetic field of 1.6 MA/m (hatched columns) for: *a, b, c* — martensite packets; *d, e, f* — twinned martensite crystals

Figure 6 shows that processing in a magnetic field refines the regions containing twinned martensite crystals, while their formfactor remains unchanged. The increased dispersity is also linked to the catalytic effect of the magnetic field on the multiple and widespread nucleation of martensite. The formation of lath martensite (formed at higher temperatures [19, 20]) is intensified, which causes the phenomenon of cold hardening of γ -phase.

Hardness values were consistently higher after magnetic field assisted processing than after processing without a field (Fig. 7). These results are attributed to a reduction in martensite crystal dimensions, lower volume fractions of austenite A_{ocr} and non martensitic phases, as well as dispersion hardening (during quenching, intermediate carbide precipitates directly [21, 22]). The exception is the hardness in the butt region, which drops under magnetic quenching due to intensified self-tempering [23, 24] in the larger section of the component.

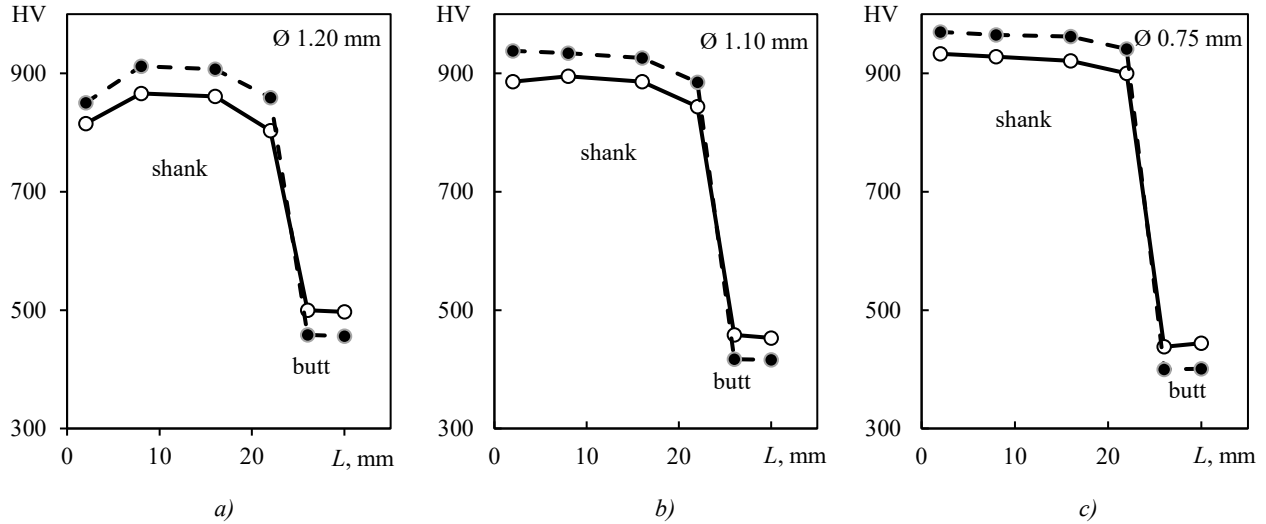


Fig. 7. Results of measuring needle hardness by Vickers method (normal hardening — solid line; hardening in magnetic field $H = 0.8$ MA/m — dashed line): a — $\varnothing 1.20$ mm; b — $\varnothing 1.10$ mm; c — $\varnothing 0.75$ mm

Examination of the l value of products after magnetic field assisted heat treatment showed no warping beyond the technical specifications ($l < l_0$), with the angular distribution φ being uniform across all diameters. Representative data for the $\varnothing 0.65$ mm diameter — which exhibited the most severe warping under standard processing — are presented in Figure 8. All needles displayed warping $l < l_0/2$ ($l_0 = 0.1$ mm), and two thirds also met the stricter condition $l < l_0/4$. Post quenching and tempering hardness values remained largely unchanged, whilst with a slight decrease (Fig. 8, b).

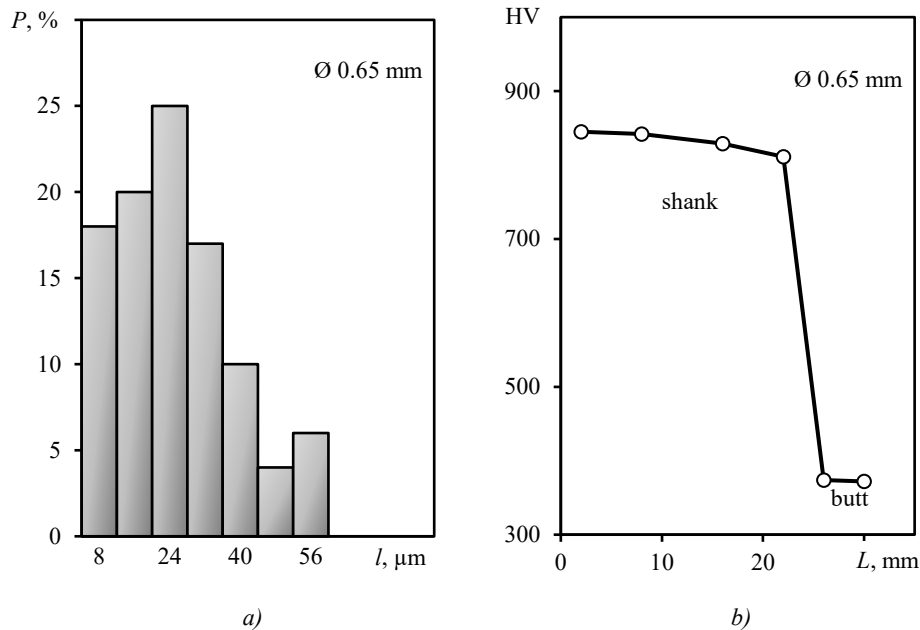


Fig. 8. Distribution of values for the product after MFHT and tempering: a — warping value; b — hardness

In the MFHT treatment mode, no intermediate straightening operations were performed. Thus, the substantial reduction in radial runout arose solely from internal mechanisms during MFHT. The key factors were superplasticity [25] occurring in steel just above the martensite start temperature, and the direct constraint of the needle along the vertical axis by the magnetic flux — an effect governed by the design of the proposed setup [15] for individual MFHT processing of parts with ratio $L/D > 10$.

Since intermediate straightening operations were excluded in MFHT, the fatigue limit of the products was impacted. The studied values σ_{-1} (Fig. 9) measured for needles with a radial runout $l \approx 25 \mu\text{m}$ were higher across all diameters compared to those obtained after standard processing.

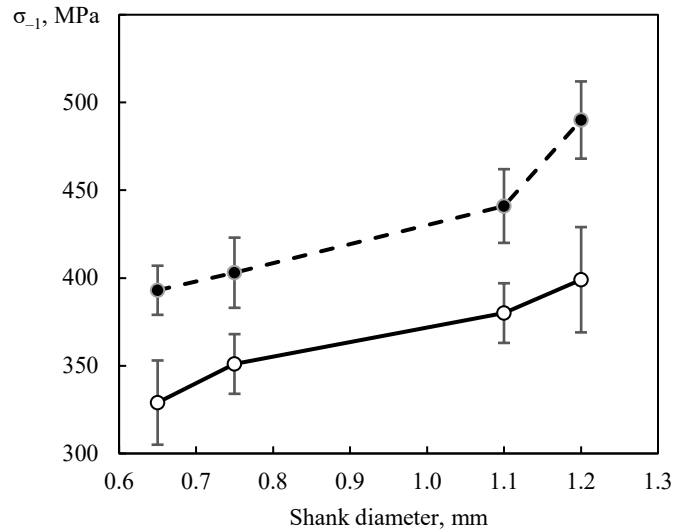


Fig. 9. Fatigue limit of products with $l \approx 25 \mu\text{m}$: standard processing with straightening operations (solid line); MFHT (dashed line)

Discussion. The data presented in Figures 1 and 2 reveal a clear correlation between needle shank bending and its stiffness. Larger-diameter needles exhibit higher shank stiffness relative to the butt, which corresponds to reduced warping susceptibility (primarily caused by groove milling). After machining, large-diameter needles showed $l \leq l_0$ values — that is, they remained within acceptable tolerances — while the angular distribution φ deviations was uniform across all directions.

After quenching, smaller-size products exhibited preferential deviation along the milled groove (in either direction). This type of warping results from an oriented internal stress state in the component originating from machining and the subsequent straightening operation. Since heating does not eliminate these stresses, they combine with quenching deformations and ultimately cause the tip to deviate at a specific angle.

The tempering processes (Figs. 3–4) slightly reduce values l across all diameters, though for small diameters, these values remain outside the acceptable range, and the prevailing distribution by φ is preserved.

Table 2 shows that machining induces a change in the stress state of the component that leads to a substantial degradation in its performance properties. Thus, eliminating warping (and, consequently, the need for straightening) can improve the performance properties of the products [26]. Deformation-free quenching is made possible through a form of internal straightening (Figs. 5, 6) due to the generation of stress-induced martensite crystals (under the impact of a magnetic field in the superplastic range) and the oriented hardening of needles along the magnetic flux lines.

The statistical data presented in Figure 6 demonstrate refinement of the martensitic phase (both lath and twinned morphologies), the overall packet structure, and separate crystals when quenching is performed in a magnetic field. The dispersion, respectively, increases the specific surface area of the boundary and subboundary — dislocation barriers for plastic deformation are created. Peak stresses are reduced and more homogeneously distributed when regions of dislocation pile-up are fragmented and martensite packets are dispersed more uniformly. Consequently, magnetic field quenching produces a martensitic microstructure that offers greater potential for both strength and ductility, resulting in superior overall properties following MFHT treatment.

From the results of the study on the effect of low tempering (Figs. 3, 4, 8), it can be concluded that while it reduces the level of hardening stresses, it does not completely eradicate radial runouts.

The research results of the fatigue limit (Fig. 9) showed its increase during processing in a magnetic field, in comparison with the serial mode, which involved mechanical processing to eliminate warping.

Conclusion. It has been established that mechanical straightening operations used to eliminate warping create a stress pattern that reduces significantly the performance characteristics of products (fatigue limit can drop to 370 MPa, residual deformation can reach 0.40 mm).

Experimental evidence has shown that the MFHT hardening technology, based on quenching steel in a magnetic field, eliminates radial runouts in rod-shaped products ($L/D > 10$). The internal straightening process, implemented through a specified MFHT processing scheme, eliminates the need for conventional machining, which reduces the product performance characteristics.

This is accomplished, firstly, through the direct vertical constraint of the needle during processing by the magnetic flux vector, and secondly, via the effect of the magnetic field on the quenching processes themselves (increasing martensite dispersion). Compared to the standard mode, an increase in the fatigue limit of an average of ~82 MPa was observed, while warping values (with a twofold safety margin) did not exceed the technical requirements (0.10 mm).

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