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Effect of deformation thermocyclic treatment and normalizing on the mechanical properties of sheet Steel 10

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ABSTRACT

Introduction. This paper investigates the influence of deformation thermocyclic treatment (*DCT*) and subsequent normalizing on the mechanical properties and microstructure of low-carbon *Steel 10*. Low-carbon steels are widely used in engineering due to its high ductility; however, traditional heat treatment methods have a limited effect on its strength. *Steel 10*, with slightly increased carbon content, is more susceptible to heat treatment, which allows for optimizing the balance between strength and ductility. **The purpose of the work** is to determine the optimal parameters of *DCT* and normalizing for achieving the best combination of mechanical properties of sheet steel *Steel 10*. In this work, *Steel 10* samples, produced by OJSC "NKMC", were studied. **The methods of investigation** include the analysis of the chemical composition using an emission spectrometer *ARL 4460*. Samples were subjected to cyclic forging (DCT) on a hydraulic press, followed by rolling to a thickness of 3 mm. Mechanical properties (tensile strength, yield strength, elongation, and reduction of area) were determined using a testing machine *Instron 3369*. **Results and Discussion.** The results showed that *DCT* leads to grain refinement and texture reduction, which improves ductility. The optimal normalizing temperature is 900°C, providing the best combination of strength and ductility for both conventionally treated and *DCT*-treated steel. At the same time, *DCT* slightly increases the strength but significantly increases the elongation (by 15 %) and the reduction of area (by 11%). Subsequent normalizing of the *DCT*-steel significantly increases ductility (by more than 50 %) and reduces strength. The data obtained allow for optimizing the technological process to achieve the desired balance of properties.

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Inrtoduction

Low-carbon steels, such as grades 05, 08, and 10 (according to *GOST 1050*), are a preferred construction material for a wide temperature range from −40 °C to +450 °C due to their excellent ductility. This group of steels is characterized by excellent weldability, resistance to flake formation, and absence of temper embrittlement during operation. Their high ductility makes these steels indispensable in the manufacture of machine parts and assemblies requiring significant plastic deformation, such as cold forming, drawing, bending, and other types of pressure shaping. These steels are typically used for parts and assemblies subjected to moderate static loads under operating conditions [1–3].

In conventional metalworking, mild steels, owing to their low carbon content, are not traditionally subjected to intensive heat treatment to increase their strength. This is because standard heat-treatment methods, such as quenching and tempering, have little effect on the strength properties of these steels. The reason for this is the limited ability to change the microstructure of steels with low carbon and alloying element content. The increase in strength is often accompanied by a significant decrease in ductility, making this approach impractical for most applications. Low carbon steels are valued primarily for their high ductility and weldability, which are essential for various pressure processing techniques [4, 5].

However, *Steel 10*, with a slightly higher carbon content (0.07–0.14 wt. %), represents an exception to this rule. A small, but sufficient, increase in carbon content opens up the possibility of more efficient heat-treatment methods. Normalizing, quenching followed by high-temperature tempering, and annealing have a marked effect on the microstructure of *Steel 10*, leading to a finer and more uniform distribution of carbides and, consequently, to improved mechanical properties [6]. These methods make it possible to adjust the balance between strength and ductility, allowing the selection of the optimal processing mode for specific operating conditions. The application of these methods allows to obtain steel with improved strength properties without significantly sacrificing its ductility [7–9].

To further improve the performance properties of *Steel 10*, particularly to achieve higher strength and fatigue resistance, a promising direction is the use of deformation thermocycling treatment (*DTCT*) in combination with subsequent heat treatment. *DTCT*, which involves the cyclic application of high temperature and plastic deformation, allows one to achieve a finer and more refined microstructure, reduce internal stresses, and improve the uniformity of properties across the cross-section of the product [11–14]. Combining *DTCT* with subsequent normalizing or quenching with high-temperature tempering allows one to obtain steel with significantly improved mechanical properties optimized for specific working conditions, which expands the application area of low-carbon steels.

Studies [1–10] indicate the beneficial effect of *DTCT* not only on mechanical properties but also on a wide range of material properties. This method has a beneficial effect on the physical, technological, and operational properties of a variety of materials, ranging from cast irons [15] to steels with different chemical compositions [1, 2, 16–18]. The effectiveness of *DTCT* has also been confirmed by studies on aluminum alloys, in particular, hypereutectic silumins [4–6]. This integrated approach allows one to optimize the internal structure of the material, creating more favorable conditions for stress distribution and improving ductility and strength.

The mechanisms of property improvement achieved through *DTCT* involve a complex process of internal stress redistribution and microstructural changes within the metal. As a result, applying this method can significantly improve the strength, ductility, corrosion resistance, and durability of products. The use of *DTCT* in combination with subsequent heat treatment opens new perspectives for optimizing the properties of steels, especially when it is necessary to achieve a balance of strength and ductility properties [19–20]. Further research should aim to identify the optimal *DTCT* modes to achieve the maximum effect, quantifying the effect of different treatment parameters on the structure and mechanical properties of *Steel 10*. It is also necessary to consider the effect of *DTCT* on other performance characteristics, such as wear resistance and fatigue strength.

In this regard, a study was carried out to investigate the effect of the *DTCT* mode, including thermocyclic deformation (forging) at a temperature above the Ac_3 point, and subsequent normalizing on the mechanical properties of *Steel 10* plate.

The **aim of the work** was to determine the optimal parameters of *DTCT* to achieve maximum improvement of the mechanical properties of this steel, which will allow us to expand its field of application and create more reliable and durable engineering products. To achieve this aim, several tasks were undertaken, such as manufacturing samples, conducting mechanical tests, and analyzing changes in the mechanical properties of steel under the influence of *DTCT*. The results obtained will allow us to justify the application of *DTCT* to improve the properties of *Steel 10* plate and other low-carbon steels.

Methods and materials

Steel 10, produced at Novokuznetsk Metallurgical Complex (*OJSC NKMC,*), was selected as the starting material for this study. This steel was chosen due to its widespread use in mechanical engineering and relatively low cost, making it an attractive subject for studying the effect of various processing methods on its mechanical and microstructural properties. To accurately determine the chemical composition of the steel under study, a modern spectral analysis method was used. Specifically, an *ARL 4460* emission spectrometer was used to determine the quantitative content of various elements in the steel. The obtained chemical composition data were used for comparison with literature data and to assess the steel's compliance with the declared standards (Table 1).

Table 1

Chemical composition of *Steel 10* being treated

Steel	Element content, % (weight)							
	C	*Mn*	*Si*	*P*	*Cr*	*S*	*Cu*	*Ni*
10	0.134	0.422	0.226	0.0139	0.048	0.0181	0.198	0.041

During an experiment conducted at JSC West Siberian Metallurgical Complex (Novokuznetsk), a steel slab measuring 900 mm × 700 mm × 500 mm underwent cyclic forging using a single-pass drawing method on a 20 MN hydraulic press. The deformation process was performed at a heating temperature of 1,250 °C, with the slab held in the furnace for 2 hours prior to forging (excluding heating time). The holding time was carefully selected to ensure uniform heating of the slab throughout its volume. During the experiment, 10 deformation cycles were performed, resulting in a significant change in the structure and properties of the starting material. As a result of repeated deformation, the thickness of the billet after deformation thermocyclic treatment (*DTCT*) was reduced to 300–310 mm, demonstrating a substantial degree of plastic deformation.

Following *DTCT*, the resulting billets were further processed by rolling at JSC Novosibirsk Metallurgical Plant named after A.N. Kuzmin (Novosibirsk). The rolling was performed according to an industrial technological mode to obtain sheet material of a specified thickness. The rolling process resulted in sheets with a thickness of 3 mm, exhibiting altered properties compared to the initial slab. This change in properties is a consequence of the combined effect of deformation and heat treatment, which constitute the essence of *DTCT*.

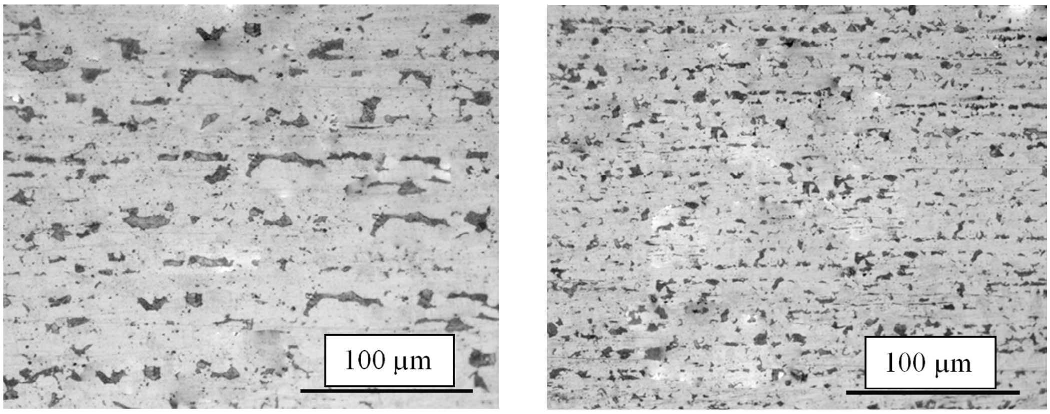
To comprehensively evaluate the effect of deformation thermocycling treatment (*DTCT*) on the properties of sheet steel, comprehensive mechanical testing was performed on the resulting material. Flat specimens with a thickness of 3 mm, fabricated from sheet steel that had undergone *DTCT* and subsequent rolling, were used. The tests were conducted on an *Instron 3369* universal testing machine. During testing, key mechanical properties of the resulting sheet steel were determined. These included: ultimate strength (σ_u), yield strength (σ_y), percentage elongation (δ), and percentage reduction in area (ψ).

Further details regarding the technological process of sheet steel production using *DTCT*, including forging parameters, heating and cooling modes, and rolling parameters, are provided in [7].

Results and Discussion

A previous study [2] indicated that employing pre-deformation thermocyclic forging prior to rolling *Steel 10* plate promotes the retention of the ferrite-pearlite microstructure (Fig. 1). It is important to note that pre-deformation thermocyclic treatment (*DTCT*) significantly influences pearlite morphology. Specifically, *DTCT* results in a reduction in pearlite colony size, a decrease in their volume fraction, and a weakening of texture, manifested as a decrease in the degree of orientation of pearlite colonies along the rolling direction. These *DTCT*-induced microstructural changes lead to a notable improvement in mechanical properties.

Moreover, the results of the study [2] showed that applying *DTCT* prior to rolling leads to a significant, nearly 30 % increase in the strength of hot-rolled *Steel 10* sheet. This is evidenced by the increase in ultimate strength from 370 to 478 MPa and yield strength from 305 to 390 MPa (Fig. 1). It should be emphasized that such a significant increase in strength is achieved with a minimal and acceptable decrease in the material's ductility. The application of pre-deformation thermocyclic treatment (*DTCT*) demonstrates significant potential for improving the mechanical properties of *Steel 10*, making this method highly promising for industrial applications. The strength improvement achieved is not a random outcome of the treatment but results from fundamental changes in the material's microstructure. These changes, in turn, significantly influence the steel's deformation and fracture mechanisms.



a *b*

Fig. 1. Microstructure of the studied samples made of *Steel 10* (sheet thickness 3 mm) obtained using industrial technology (*a*) and using thermal cycling forging (*b*)

Two key microstructural effects underlie the strength improvement achieved by *DTCT*. Firstly, *DTCT* promotes grain refinement in the steel. A finer grain size increases the grain boundary area, which acts as a barrier to dislocation movement, the primary mechanism of plastic deformation [2]. This impedes plastic deformation, thereby increasing the material's strength. Finer grain size also contributes to increased yield strength and hardness of the steel. Secondly, *DTCT* effectively reduces texture in the material. Texture, or the preferred crystallographic orientation, often arises during metal forming and can lead to anisotropic mechanical properties. The texture reduction achieved by *DTCT* results in a more isotropic material, with more uniform properties in all directions. This enhances the steel's resistance to deformation and increases its reliability under complex stress conditions.

Thus, the combination of grain refinement and texture reduction achieved by *DTCT* provides a comprehensive improvement in mechanical properties, significantly increasing strength while maintaining high ductility of the steel. This makes *DTCT* an effective tool for improving the quality and expanding the application range of *Steel 10*.

As a continuation of this study, the effect of normalizing temperature on the microstructure and mechanical properties of hot-rolled *Steel 10* sheets produced both by the conventional industrial mode and with the application of *DTCT* was investigated. The experiments were conducted across a range of normalizing temperatures from 600 to 1,000 °C, with a holding time of 10 hours at each temperature. This extended holding time ensured the attainment of thermodynamic equilibrium at the specified temperature. The results of the study showed that altering the normalizing temperature significantly affects the steel's microstructure [2], with increasing temperature having the most pronounced effect. It was found that increasing the normalizing temperature up to 900 °C leads to a noticeable refinement of pearlite colonies within the steel's microstructure. This, in turn, affects the mechanical properties, necessitating further investigation of the correlations between the temperature and time parameters of normalizing and changes in strength and ductility. Additional studies will enable the optimization of the technological process to achieve the maximum benefit from the application of *DTCT* and subsequent normalizing.

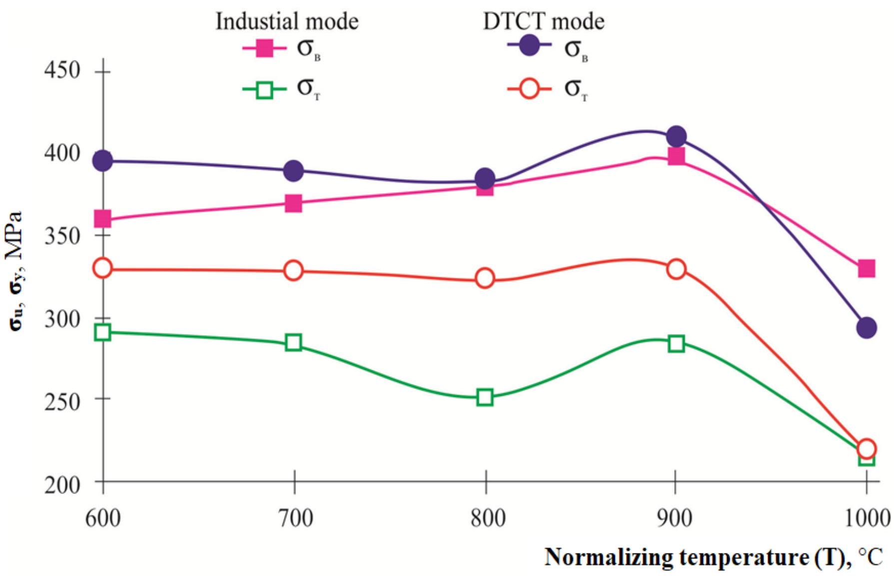
The process of structural changes in steel during normalizing proceeds with varying intensity depending on the pretreatment. It was found that steel subjected to pre-forging exhibits more active structural rearrangements during normalizing than steel that has not undergone forging. This is attributed to the higher dislocation density and higher strain energy accumulated in the steel structure after forging. These structural defects act as nucleation sites for the formation of new grains at high normalizing temperatures.

Increasing the normalizing temperature up to 1,000 °C results in an increase in grain size and, consequently, coarsening of the steel structure, regardless of whether a prior *DTCT* was applied. This is caused by recrystallization and grain growth processes at high temperatures. The coarsening of the structure is accompanied by a decrease in strength properties and an increase in the ductility of the material. Therefore, an optimal normalizing temperature exists at which the best combination of strength and ductility is achieved.

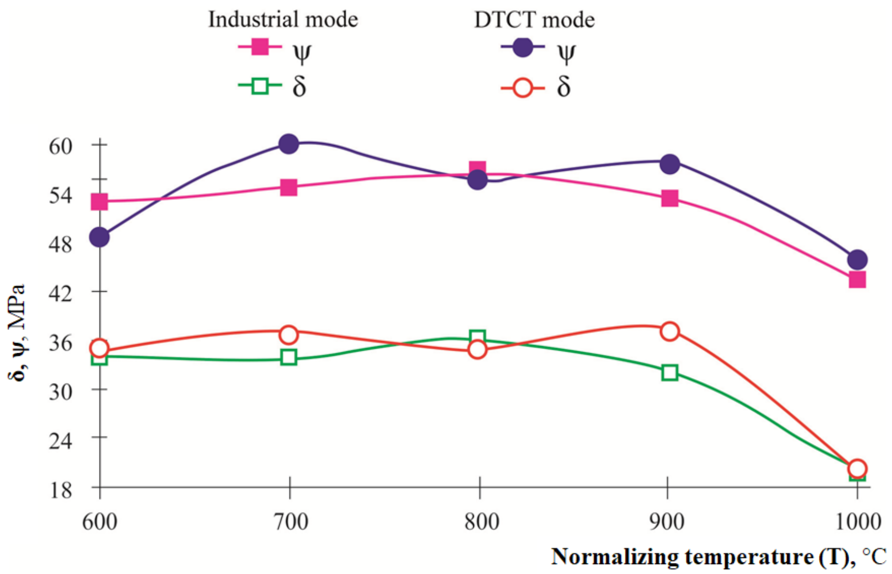
Analysis of the results obtained (Fig. 2, *a*, *b*), demonstrating the influence of normalizing temperature on the properties of hot-rolled *Steel 10*, revealed an optimal normalizing temperature of 900 °C. At this temperature, the most favorable combination of strength and ductility is achieved, both for steel produced by conventional technology and for steel pre-treated by deformation thermocycling (*DTCT*). Notably, the application of *DTCT* does not result in a substantial increase in strength properties compared to conventionally hot-rolled steel. However, a significant increase in ductility is observed. Specifically, an increase in relative elongation of approximately 15 % and a relative reduction in area of 11 % are observed with the use of *DTCT*. These considerable improvements in ductility clearly demonstrate the potential of *DTCT* as a method for enhancing the ductility of steel without significant strength degradation. This is a critical result, as many processes, such as cold forming or deep drawing, demand high ductility without a significant reduction in strength.

The data suggest that *DTCT* modifies the steel microstructure in a manner that enhances its ability to undergo plastic deformation. This is probably due to the reduction of internal stresses and the redistribution of steel phase composition, leading to a more uniform distribution of deformation throughout the material volume. Overall, the results of the study confirm the feasibility of using *DTCT* in conjunction with normalizing to produce sheet *Steel 10* with an improved balance of strength and ductility, particularly if the final product requires high ductility.

Subsequent normalizing of *DTCT*-pretreated steel induces significant changes in its properties. A reduction in strength of approximately 15 % is observed, indicating a decrease in deformation resistance. Concurrently, the ductility of the steel increases significantly — by more than 50 % compared to the initial hot-rolled state. This change in properties is attributed to microstructural rearrangements occurring during normalizing following *DTCT*. The secondary heat treatment further refines the crystalline structure, which, in turn, reduces strength but significantly increases ductility. Furthermore, the normalizing process effectively relieves residual stresses accumulated in the steel during *DTCT*. The release of these stresses contributes to improved ductility, making the material more amenable to further forming operations. Thus, the combined effects of *DTCT* and normalizing produce a highly ductile material, which can be particularly valuable in the production of parts requiring substantial plastic deformation. This significant increase in ductility



a



b

Fig. 2. Influence of normalizing temperature (duration 10 hours) on the mechanical properties of hot-rolled *Steel 10* sheet, manufactured according to the industrial mode and using *DCT*:

a – σ_u, σ_y; *b* – δ, ψ

is particularly important when high plastic deformation rates are required in metal forming. Therefore, selecting the optimal normalizing and *DTCT* modes allows for tailoring the strength-ductility balance of *Steel 10* steel to meet the requirements of a specific application.

Careful analysis of the mechanical property data, correlated with the process data, has enabled us to determine optimal *DTCT* parameters to ensure that the required mechanical properties of the final product are achieved. This includes not only selecting optimal forging parameters such as temperature and degree of deformation but also optimizing subsequent heat treatment modes to ensure the best combination of strength, ductility, impact toughness, and other required properties for specific operating conditions of products made of this steel.

Based on the results obtained, it is possible to develop recommendations for the industrial implementation of *DTCT* to improve the quality and performance characteristics of sheet *Steel 10*.

Conclusions

The study has demonstrated that the utilization of deformation thermocycling treatment (*DTCT*) in conjunction with subsequent normalizing enables effective control of the mechanical properties of sheet *Steel 10*, thereby expanding its application range.

Preliminary *DTCT*, while resulting in a modest increase in strength (approximately 30 %), leads to a significant enhancement of ductility in hot-rolled *Steel 10*. Relative elongation and reduction in area increase by approximately 15 % and 11 %, respectively. This positions *DTCT* as a promising method for producing steel with an improved combination of strength and ductility, particularly crucial for cold forming processes.

This study confirms the high effectiveness of *DTCT* as a pretreatment method for sheet *Steel 10* prior to subsequent normalizing. The combined effect of these methods allows for achieving a substantial improvement in ductility while maintaining acceptable strength. The results obtained open new avenues for optimizing the technological process of producing sheet *Steel 10*, expanding its range of application in mechanical engineering and other industries.

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Conflicts of Interest

The authors declare no conflict of interest.