STRUCTURAL CHANGES OCCURRING DURING THERMOMECHANICAL TREATMENT OF STEEL AND THEIR INFLUENCE ON THE MECHANICAL PROPERTIES*

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Thermomechanical treatment (TMT) is a treatment after which hardening or any other change in the properties is the result of the simultaneous influence of plastic deformation (cold working) and phase (structural) transformations.

There are many variations of TMT; they differ by the type of structural transformation and by the sequence of plastic deformation and heat treatment. Therefore, we shall classify the different types of TMT before investigating the influence of TMT on the structure and properties of steel.

Classification of TMT. Thermomechanical treatments can be divided into two classes: A) TMT of metals and alloys which undergo polymorphic transformations (ordinary steels and titanium alloys); B) TMT of alloys which do not undergo polymorphic transformations but contain soluble excess phases (some austenite steels, nickel heat-resistant alloys—nimonics, alloys of high-melting-point metals, etc.). The hardening of these alloys is due to aging. The aging of the deformed matrix is different, and therefore the properties of the material are different after TMT than after aging of the matrix which is not cold hardened (solid solution).

The purpose, the methods, and the resulting change in the properties resulting from the two types of TMT are different, and therefore the two types must be examined separately. Also, it is widely accepted that the B type of TMT should not be considered a TMT, and should be called differently [1]. Therefore, we shall examine here only the A type of TMT.

Plastic deformation of the phase which has undergone transformation may be carried out before the transformation (a), during the transformation (b), and after the transformation (c). Many methods, including the older methods of treatment, belong to the (c) category. In this case one may assume that the heat treatment prepares the structure for deformation. All the methods of manufacturing cold-worked articles using several passes include intermediate heat treatment and can be formally included in this type of thermomechanical treatment (Ac) even if the treatment does not produce a high strength.

However, the best mechanical characteristics are obtained with the (Ac) method. I speak here about the old process—patenting—which consists in producing a fine ductile pearlite by heat treatment followed by drawing with a high degree of plastic deformation. The strength of wire 0.1 mm in diameter drawn by using 98% deformation exceeds 450 kg/mm^2 [2].

If the structure before deformation consists of martensite then deformations cannot exceed 10%, but even then deformation promotes strengthening. This type of treatment, consisting in quenching to martensite with subsequent deformation and tempering ("marforming" in American terminology) appears to be very promising [3, 4]. The qualitative difference between patenting and marforming is that patenting hardens the metal as the result of deformation, while marforming hardens the metal as the result of heat treatment, since the initial structures are different in these two cases.

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TABLE 1. Classification of Thermomechanical Treatments

Class	Type (successive operation)	State of deformed matrix
A. Alloy undergoes polymorphic transformation	a. Deformation before transformation (TMT proper)	Deformation at a temperature above recrystallization temperature (HTTMT).
		Deformation below recrystallization temperature (LTTMT)
		Deformation before transformation during heating (PTMT)
	b. Deformation during transformation	–
	c. Deformation after transformation	Deformation of the products of diffusional transformation (including patenting)
		Deformation of the products of martensitic transformation (including marforming)
B. Alloy does not undergo polymorphic transformation	a. Deformation before aging	Deformation of stable solid solution above the recrystallization temperature
		Deformation of supercooled solid solution below the recrystallization temperature
	b. Deformation during aging	–
	c. Deformation of aged alloy	–

Transformations (polymorphic) during deformation (Ab) occur in a number of alloys, particularly as the result of deformation of austenitic steels at temperatures below 0°C (more precisely, below the M_c point). In this case one can reach very high strength and during the phase (martensitic) transformation the steel has an anomalously high ductility. This type of treatment is used to strengthen austenitic stainless steel. In this case the transformation leads to several singularities. I made a report on the structural transformations occurring during deformation of austenitic stainless steel at the Metal Sciences department of Silezia Polytechnical Institute (May, 1959) [5].

In recent years the (Aa) process has attracted particular attention. This TMT is characterized by the fact that the transformation occurs after deformation, i.e., the cold-hardened or only partly recrystallized matrix undergoes phase transformation.

Alloys can be deformed above or below the recrystallization temperature. In the first case (high temperature thermomechanical treatment—HTTMT) cold-working is not completely preserved. The recrystallization processes have time to occur to a certain degree. The so-called pause, i.e., the time between the end of the deformation and immersion in the quenching medium, acquires great importance. In the second case (low temperature thermomechanical treatment—LTTMT) these problems, important in the case of HTTMT, do not occur, but other problems are created (the difficulty of deformation because of low temperature, structural instability of austenite, variation of temperature, etc.).

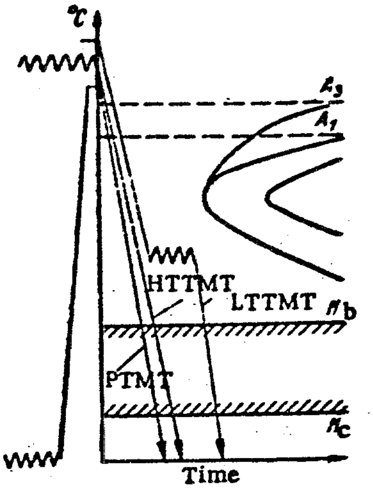

Fig. 1. Classification of thermomechanical treatments.

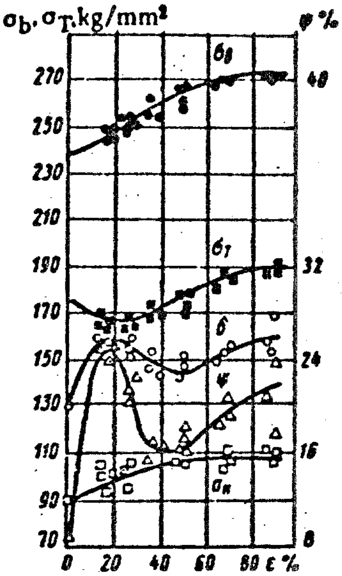

Fig. 2. Effect of the degree of deformation during HTTMT on the mechanical properties of 50KhN4MA steel tempered at 100°C [9].

TABLE 2. Mechanical Properties of 50KhN4MA Steel After TMT [9]

Treatment conditions	σ_b^2	$\sigma_{0.2}$	δ	ψ	a_H, kgm/cm²
	kg/mm²		%		
Quenching + tempering at 100°C	240	175	6	9	2
HTTMT (90%) + tempering at 100°C	270	190	9	22	4
LTTMT (35%) + tempering at 100°C	260	175	8	18	3

In the case of steel one more type of TMT is possible [6, 7]. This is the preliminary thermomechanical treatment (PTMT), consisting of plastic deformation before heating to austenization either by low or high temperature TMT. When the heating rate is high then the results of cold working (structural defects created by deformation) are preserved and this is responsible for additional strengthening of the material. The different thermomechanical treatments are classified in Table 1.

The diagrams of high temperature, low temperature, and preliminary thermomechanical treatments are shown in Fig. 1. For simplicity of presentation we assume that the A_1-A_3 interval coincides with the recrystallization interval. The zigzag lines indicate deformation.

Influence of the (Aa) TMT on the mechanical properties. The strengthening resulting from TMT is the sum of the strengthening resulting from heat treatment (martensitic transformation) and the strengthening resulting from plastic deformation. Under constant transformation conditions the total strengthening increases with increasing degrees of deformation of the austenite or, more precisely, with the degree of strengthening of austenite, as was shown in [8]. Nevertheless, it is difficult to determine the strengthening induced by each factor separately.

To determine the effect of plastic deformation it is necessary that the martensitic transformation under the influence of plastic deformation remain constant; this is impossible, since plastic deformation changes not only the amount of subsequent martensitic transformation but also the composition of the austenite.

TABLE 3. Strengthening of Steel by TMT

Conditions	Tempering temp., °C	Carbon, %	σ_b, kg/mm²	$\Delta\sigma_c$		Reference
				kg per mm²	%	
—	100	0,50	240	—	—	[9]
HTTMT 90%	100	0,50	270	30	12	
LTTMT 35%	100	0,50	260	20	8	
—	230	0,38	200	—	—	[13]
LTTMT 70%	230	0,38	230	30	15	
—	300	0,38	210	—	—	[14]
	300	0,38	245	35	17	
—	200	0,34	180	—	—	]11]
LTTMT 80%	200	0.34	200	20	11	
HTTMT 80%	200	0.34	210	30	17	
—	100	0,41	215	—	—	[8]
LTTMT 80%	100	0,41	255	45	18	

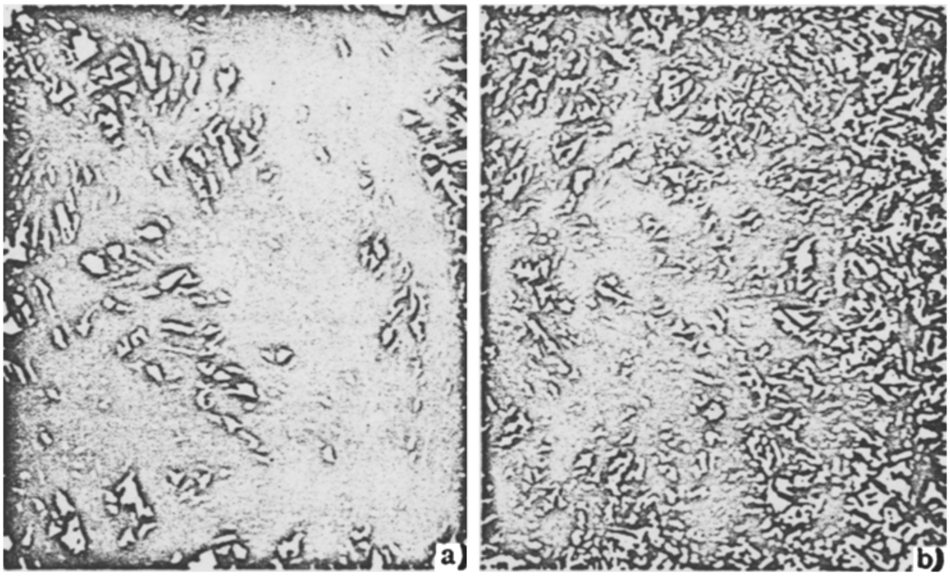

Fig. 3. Structure of U12 steel (x600): a) quenched; b) HTTMT.

Therefore, depending on the degree of plastic deformation, the final mechanical properties (particularly ductility and resilience) change according to a rather complex law (Fig. 2) [9]. The complex dependence of the ductility on the degree of plastic deformation was shown in [10-12]. However, if one avoids the unfavorable deformation interval then all the mechanical characteristics are improved as the result of TMT under optimum conditions (Table 2).

One can note a relatively small increment in strength ($\Delta\sigma_b$ = 20-30 kg/mm², $\Delta\sigma_{0.2}$ = 0-15 kg/mm²) which is approximately 10%. This result is confirmed by the results of many investigations concerning the influence of TMT. In Table 3 we give the maximum values of strength resulting from high and low temperature TMT and also the results obtained by different authors in the absence of the deformation of austenite.

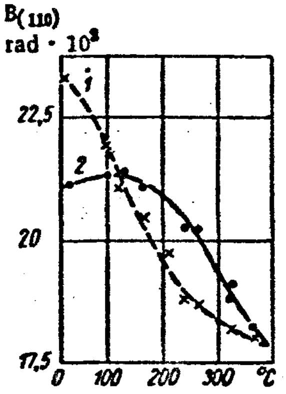

Fig. 4. Width of the [110] x-ray fringes as a function of the tempering temperature: 1) quenched; 2) HTTMT (90%) [15].

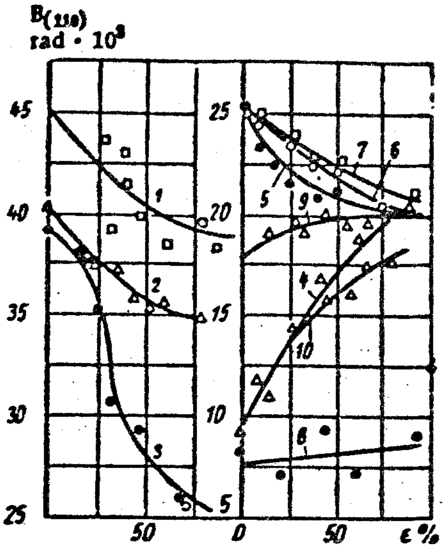

Fig. 5. Effect of the degree of plastic deformation on the width of the [110] x-ray fringes. 1) U12 steel, HTTMT at 1100°C; 2,3) U12 steel, HTTMT at 900°C (1 and 2 additionally treated at subzero temperature); 5,6,7) 50KhN4M steel, HTTMT at 900°C; 1-6) quenched steels; 8) Armco iron, deformed at 950°C; 9) after tempering at 200°C; 10,11) titanium alloys (1.3% Ti, 1.4% Mn), HTTMT [15].

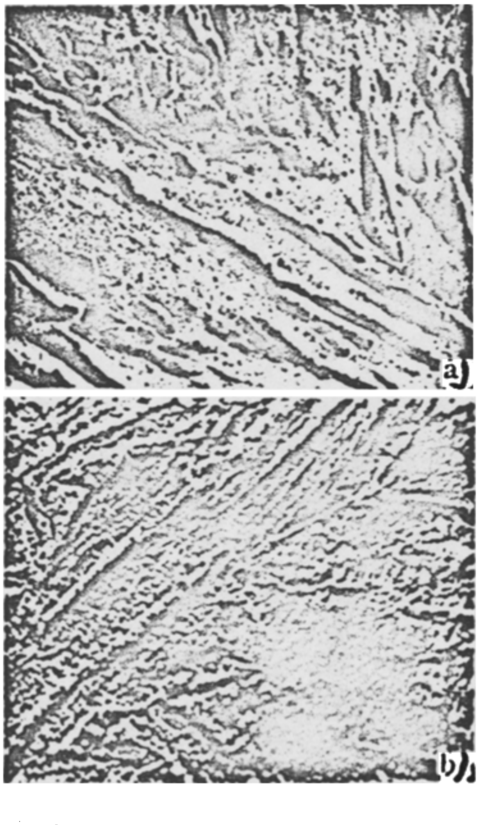

Fig. 6. Microstructure of U12 steel (x 12,000): a) quenched; b) HTTMT (70%) [16].

Such small increases in strength may lead to the conclusion that TMT is not an advantageous process, particularly if one takes into account the complexity of the technological process required by this treatment. Thermomechanical treatments of both types, particularly high temperature TMT, sharply increase the ductility (see Table 2). The steel treated to obtain a strength $\sigma_b = 240$ kg/mm² with $\psi = 9\%$ and $a_H = 2$ kgm/cm² is not sufficiently reliable for construction purposes. One can use the steel after heat treatment if the strength is no higher than $\sigma_b = 180$ kg/mm² because the steel having a higher strength has low ductility and resilience (more precisely, low resistence to brittle rupture). But with TMT the steel can be used with σ_b up to 250-270 kg/mm². The difference in the strength is 70-90 kg/mm², which is about 40-50% of the strengthening, and this is considerable.

Thus, TMT improves all the mechanical properties (particularly ductility and resilience) and this makes it possible to utilize the strength resulting from this treatment.

Influence of TMT on the fine structure. The influence of TMT on the properties of steel is apparently the result of the influence of the deformation on the structure which is preserved even after the transformation (austenite into martensite and tempering of the martensite).

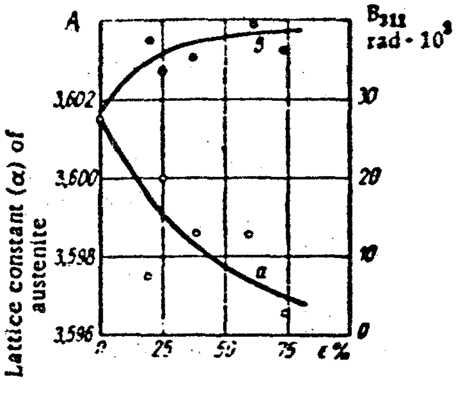

Fig. 7. Effect of the degree of deformation during HTTMT on the lattice constant of austenite and the width of the x-ray fringes. U12 steel [16].

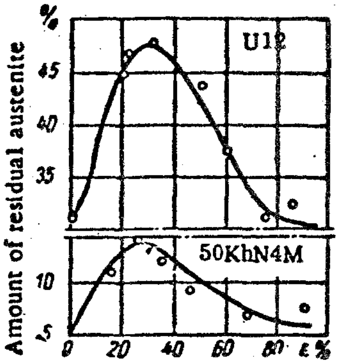

Fig. 8. Effect of the degree of deformation on the amount of residual austenite. HTTMT at 900°C [15].

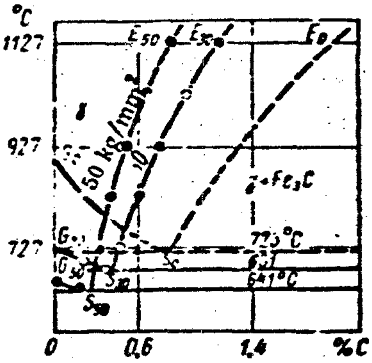

Fig. 9. Iron-carbon diagram. The magnitude of the compression stress is indicated on the diagram [21].

The influence of TMT on the structure is complex and can hardly be explained by a single factor.

Of course, the fragmentation of the austenite grains has an important influence on the properties, particularly the ductility (Fig. 3).

Deformation creates imperfections of the crystal structure of austenite and these imperfections pass into the α-lattice after the austenite-martensite transformation, i.e., the total cycle of TMT creates a higher dislocation density than quenching followed by tempering. This explanation is widely accepted.

Measurements of the width of the x-ray fringes [110] which characterize the density of imperfections of the crystal structure show that the width of the fringes is smaller after TMT than after tempering at 150°C and above, and become larger than the width of the martensite lines of the steel quenched in the ordinary way (Fig. 4). X-ray studies of different materials show that in all steels the width of x-ray fringes relative to quenched metal decreases with increasing degrees of plastic deformation used in high and low temperature TMT. However, in steel tempered at 200°C, pure iron, and titanium alloys the x-ray fringes widen normally with increasing degrees of deformation (Fig. 5) [15].

The width of the x-ray fringes relative to quenched steel depends on the carbon concentration in the solution and in martensite. Therefore, if the width of the fringes decreases as the result of TMT this is due only to the fact that carbon precipitates as the result of deformation of austenite [15]. Tempering at 200°C, which leads to almost complete precipitation of carbon, shows the real influence of deformation—the increase of the width of the fringes in martensite and austenite. In materials free from carbon (iron and titanium alloys) deformation during TMT does not decrease the width of the x-ray fringes.

The precipitation of carbon in the form of small carbide particles resulting from TMT can also be revealed by other methods—by examination under an electron microscope, for example (Fig. 6), or by the decrease in the lattice constant of austenite (Fig. 7). Deformation of austenite [17, 18] makes the formation of the martensite difficult. It decreases the martensitic transformation point and increases the amount of residual austenite. This effect of plastic deformation occurs also in the case of TMT, but the amount of residual austenite begins to decrease after high degrees of plastic deformation (Fig. 8), while the temperature of the martensitic transformation increases, which is the result of another effect—"precipitation" of carbon from the austenite lattice as the result of plastic deformation.

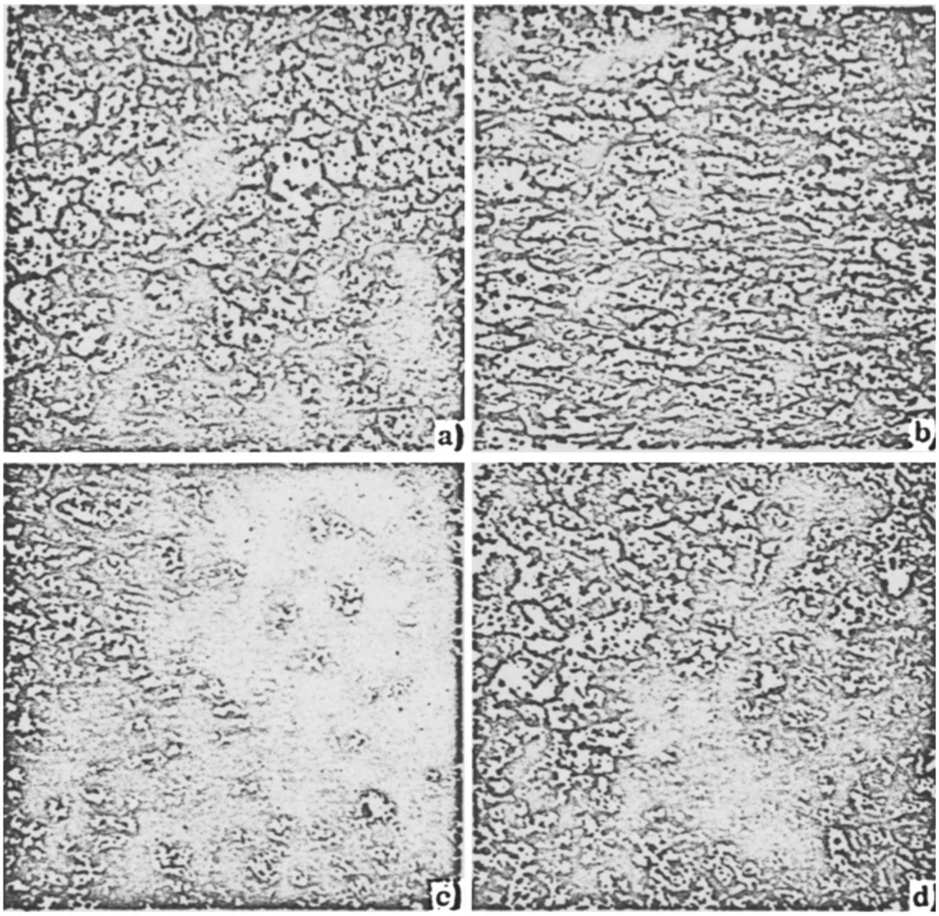

Fig. 10. Structure of 50KhN4M steel: a) quenched; b,c,d) HTTMT at 900°C and 60% swaging. Pauses: b) 1 sec; c) 6 sec; d) 10 sec.

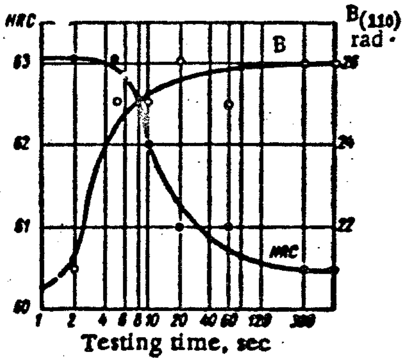

Fig. 11. Variation of the width of the [110] fringe and of the hardness with the duration of the pause during HTTMT at 900°C and 60% swaging [16].

According to modern concepts concerning the nature of the mechanical properties of heat-treated steel [19, 20], it is assumed that the higher the temperature of the martensitic transformation, the higher are the ductility and resilience of the steel, the strength remaining the same (because martensite is formed at a higher temperature and the possibility of the formation of microcracks is decreased). Therefore, TMT leading to an increase of the temperature of the martensitic transformation should contribute to the improvement of all the mechanical properties.

Thus, deformation during low and high temperature TMT leads to the precipitation of carbon from austenite, although austenite is not supersaturated in the case of high temperature TMT. The explanation of this paradoxical fact is as follows: local compression stresses are produced as the result of plastic deformation and it is well known that the SE line of the iron-carbon diagram is shifted sharply to the left (Fig. 9) and the austenite becomes supersaturated under the effect of hydrostatic compression stresses [21].

It is clear that this state is unstable. After the deformation is terminated (the pressure is relieved) at high temperature the reverse dissolution of carbides and recrystallization proceed rapidly. Experiments showed that the first process is more rapid. Recrystallization is terminated in 10 sec (50KhN4M steel, 60% deformation by impact at 900°C), while 3-5 sec suffice to restore the width of the fringes to the dimensions characteristic of the undeformed state (Figs. 10 and 11).

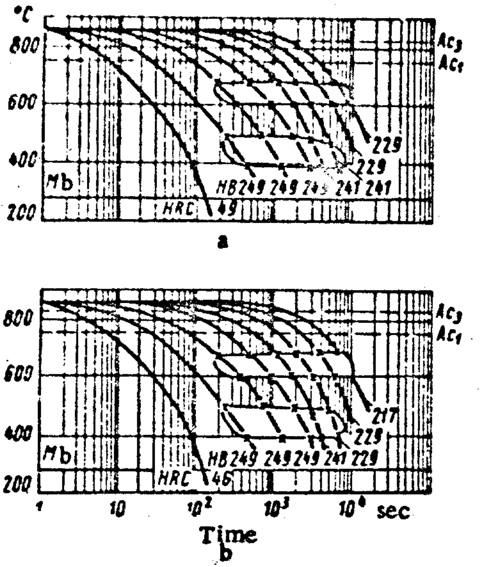

Fig. 12. Diagram of anisotropic transformation of austenite. 40KhNMA steel: a) not deformed; b) preliminary deformation (50% at 20°C) [22].

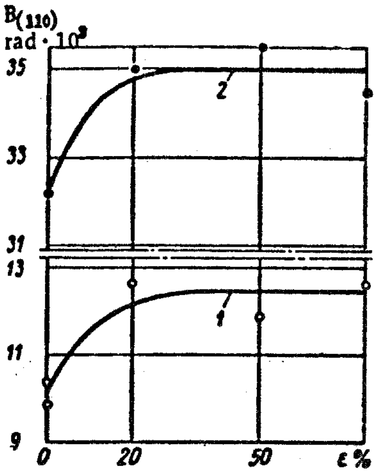

Fig. 13. Dependence of the width of the [110] fringe on the degree of preliminary deformation during PTMT: 1) before quenching; 2) after quenching.

TABLE 4. Mechanical Properties of 40KhNMA Steel (microsamples) After PTMT

Preliminary treatment	Final treatment	σ_b	$\sigma_{0.2}$	δ	ψ
		kg/mm²		%	
—	—	190	160	2.5	45
50% deformation at 20°C	Quenching + tempering at 200°C	200	175	3	50
HTTMT 25% swaging	—	215	185	3	58

Thus, the changes in the properties resulting from TMT are induced by a number of factors: fragmentation of grains, accumulation of defects during deformation, and increase of the martensitic transformation temperature. The change in the amount of residual austenite and the formation of small particles of carbides also have an important effect.

Influence of preliminary deformation. If the most important factor in strengthening induced by TMT is the accumulation of defects in the austenite because of its plastic deformation, which is preserved to some degree even after it is transformed into martensite and after tempering of martensite, then one might question whether it is possible to carry out deformation before heating to austenite and thus preserve the defects resulting from deformation after complete recrystallization: pearlite → austenite → martensite.

The results obtained in [6, 7] indicate that the structural defects resulting from the deformation of the α-lattice under more or less accelerated heating to the quenching temperature are preserved and create an additional degree of strengthening.

Investigations of preliminary thermomechanical treatment (PTMT) [22] showed that preliminary deformation preceding quenching (by different methods and to different degrees) does not affect the behavior of supercooled austenite (Fig. 12). The kinetics of the decomposition of austenite is the same in all cases. However, preliminary deformation by rolling in the α-state or creation of defects of the crystal structure by high temperature TMT after a complete cycle of heat treatment (quenching + tempering) strengthens the metal to a degree close to that resulting from TMT with deformation of austenite (Table 4). Technically, PTMT is simpler than high or low temperature TMT.

The structural defects of the α-phase produced by rolling are preserved during the transformation of the α-phase into austenite and the transformation of the austenite into martensite (Fig. 13). In this case the width of the fringes after PTMT is greater than after ordinary quenching because during PTMT it is metal in the α-state which does not contain carbon that is deformed; therefore, deformation cannot induce precipitation of the carbide phase.

It is this which constitutes the difference in the structure of steel treated by preliminary, low temperature, and high temperature thermomechanical treatments.

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