Peculiarities of deformation of thin-sheet TRIP steel under static and fatigue loading

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Abstract. The features of the deformation of austenitic-martensitic thin-sheet TRIP steel under static and fatigue loading with varying parameters of the breaking rate as well as the maximum cycle stress under cyclic loading were studied. The ten-fold increase in the tensile rate led to the decrease in the ultimate strength by ≈ 6% and the relative elongation δ from 32% to 21%, which is due to a decrease in the intensity of the formation of deformation martensite. The nature of hardening during deformation of steel under static and repeated tension is almost the same. The effect of the greatest TRIP-strengthening under loading to the yield-point stress level and physical fatigue limit were found. Preliminary fatigue loading up to σ\text{max} = 1550 MPa with N = 3000 led to the increase in the yield strength and ultimate strength by ≈200 MPa and ≈100 MPa, respectively; the relative elongation decreased by a factor of 2.

1. Introduction
The aim of improving the mechanical characteristics of structural steels remains relevant for many decades is especially urgent today, since the industry has the need to increase specific strength properties, improve technological processes, and reduce the price of finished products. In light of the above, researchers and manufacturers pay close attention to the class of steels with a metastable structure with TRIP- and / or TWIP-effect, where TRIP stands for Transformation Induced Plasticity, TWIP is Twinning-Induced Plasticity [1-6]. The determining factor in which of the effects will prevail during loading is the stacking fault energy (SFE). SFE characterizes the degree of disordering of the sequence of stacking of crystallographic planes of the crystal lattice [1]. Although many works are devoted to the study of these mechanisms at the both atomic level and microlevel [2-7], there are not many works devoted to the study of this class of alloys under static and cyclic loading.

In this work, aspects of the mechanical behavior of TRIP steel 23Kh15N5AM3-Sh were studied under static and cyclic loading with varying parameters of the rate of failure in testing under static loading conditions, as well as the maximum cycle stress under fatigue loading.

2. Objects and research methods
As an object of investigation, we used specimens of austenitic-martensitic thin-sheet TRIP steel 23Kh15N5AM3-Sh. The composition of the steel is given in Table 1. Samples were cut from a 0.28 mm thick steel strip delivered by a manufacturer. The strip was produced in several cold rolling and hot rolling steps. The degree of deformation at the last stage was about 40%. Mechanical tests were carried out using "dog bone" type specimens (Figure 1a) with gage length and width of 20 and 7 mm, respectively. Static tensile tests (with strain rates ε = 8.3 × 10^{-4} s^{-1} and 8.3 × 10^{-3} s^{-1}) and fatigue
(repeated stretching) were carried out at room temperature (≈ 293K) on an Instron 8801 universal servo-hydraulic installation. In addition to the initial specimens, specimens of steel 23Kh15N5AM3-Sh were also tested for static tension, which previously had been subjected to fatigue loading at $\sigma_{\text{max}}$-900 MPa up to $N = 107$ cycles (at the fatigue limit) and at $\sigma_{\text{max}}$-1550 MPa up to $N = 3000$. The phase composition of the samples was studied X-ray diffraction analysis using a Shimadzu XRD-600 diffractometer and CuKα radiation.

At different stages of static and fatigue loading, the surface hardness of the samples and the content of $\alpha'$-deformation martensite in the structure were measured. Vickers microhardness HV was measured at a load of 0.981 N in accordance with the State Standard GOST 9450-76.

| Table 1. Chemical composition of alloy of grade 23Kh15N5AM3-Sh (wt.%) |
|------------------|---|---|---|---|---|---|---|---|---|
| C     | Cr   | Ni | Mo  | Mn  | Si  | N   | S   | P   | Fe  |
| 0.2-0.25 | 14.5-16 | 4.8-5.8 | 2.7-3.2 | $\leq$1.0 | $\leq$0.6 | 0.03-0.07 | $\leq$0.01 | $\leq$0.015 | Balance |

Figure 1. (a) Image of a sample with dimensions in mm and (b) stress–strain curve of a steel specimen.

3. Results and discussions

The original steel samples contained $\gamma$-austenite and $\alpha'$-deformation martensite in the introduction of 57% to 43%, respectively. The average grain size in the samples before testing is about 25 µm.

Tests of specimens for static tension showed that steel is characterized by both high strength ($\sigma_u = 1800$ MPa, $\sigma_y = 1650$ MPa) and ductility $\delta \approx 30\%$. This combination of mechanical properties is achieved due to the transformation of austenite into deformation martensite under the mechanical load, the so-called TRIP effect [7, 8]. The stress-strain curve for this specimen is shown in Figure 1b. Three main stages of deformation can be selected in it: the stage of microyield, the stage of yield, and a rather long stage of strain hardening. This diagram is also shown taking into account the previously obtained results of static tension TRIP steels with a deformation martensite content of 45-65% [9].

A characteristic feature of the static deformation of this TRIP steel is the presence of a pronounced stage of microyield. The value of plastic deformation at the stage of microyield (before reaching the yield point) reaches 1%. Another distinctive feature of the static deformation of 23Kh15N5AM3 – Sh steel is the length of the yield area ($\varepsilon_y$ reaches 8%). These results are associated with the processes of twinning, shear formation, and also the formation of deformation-induced martensite [10]. The strain hardening also contributes to the length of the yield area. At the stage of monotonic strain hardening, this alloy exhibits anomalous plasticity, and the tension curve has a serrated geometry, which is explained by the Portevin-Le Chatelier effect [11]. Shear formation in combination with martensitic transformation allows the metal to deform without the formation of microcracks, and also contributes to
the fact that the stress does not decrease until the sample is completely fractured, due to the formation of micro-necks [9, 12].

In the course of testing the samples, the effect of loading rate on the behavior of the material was noticed, which can be seen on the tensile curves (Figure 2). At the higher loading rate, the yield stress remains approximately the same; the value of the ultimate strength slightly decreases (by 6%), and the significant reduction in the value of the relative elongation $\delta$ takes place (from 32% to 21%). The decrease in ultimate strength and relative elongation can be explained by the fact that at low deformation rates in this steel, the deformation-induced martensite is formed. However, with increasing rate, in this case by an order of magnitude, the shear deformation mechanism begins to dominate and the intensity of deformation martensite formation decreases; this leads to such a decrease in the mechanical characteristics [13].

![Stress–strain curve of 23Kh15N5AM3-Sh steel](image1)

**Figure 2.** Stress–strain curve of 23Kh15N5AM3-Sh steel: blue loading rate $\varepsilon = 8.3 \times 10^{-4} \text{ s}^{-1}$, green $\varepsilon = 8.3 \times 10^{-3} \text{ s}^{-1}$.

![Fatigue curve](image2)

**Figure 3.** Fatigue curve (Stress-Life Diagram) for 23Kh15N5AM3-Sh steel alloy.
The investigated features of the deformation of this TRIP steel under static loading conditions, to some extent, make it possible to evaluate the behavior of this steel under cyclic loading. The experimentally obtained fatigue curve for steel 23Kh15N5AM3-Sh is shown in Figure 3. It can be seen that most of the specimens fail in the region of a small number of loading cycles (10^4-10^5) at stresses of 900-1600 MPa. This region corresponds to the stage of microyield in the diagram of static loading (Figure 1b), which is typical for high-strength steels [14]. The physical fatigue limit σ_R = 900 MPa is clearly observed. This value of the physical fatigue limit corresponds to ≈ 50% of the strength limit for a given alloy and below the physical yield strength.

Such results can be explained by the fact that, under cyclic loading at the fatigue limit (σ_R = 900 MPa), a slight strain hardening occurs, corresponding to the strain hardening under static loading at the micro-flow stage. Therefore, the shape of the tension curve remains practically unchanged with further loading. In turn, at the maximum cycle stress σ_max = 1550 MPa, which practically corresponds to the stress of the physical yield limit, a more intense steel hardening is observed, which is associated with the successive passage of the stages of cyclic yield and strain hardening [14]. This leads to a change in the shape of the tensile curve, a decrease in plasticity indices and an increase in strength indices, as well as to a convergence of the values of the yield point and ultimate strength (figure 4). This is typical for pre-hardened metal stretching and for high-strength steels.

Figure 4. Stress–strain curves for 23Kh15N5AM3-Sh alloy after cyclic loading: a - σ_max = 900 MPa, number of cycles N = 107; b - σ_max = 1550 MPa, number of cycles N = 3000.

An assessment was made of the dependence of the hardness of the samples and the amount of α′-deformation martensite at different stages of static and fatigue loading. Under static tension until the conditional yield point σ_0.2 was reached, the content of α′-martensite in the phase composition of the steel increased due to the transformation of austenite into deformation martensite from 43 to 70%, and the most intense increase in the content from 45 to 70% was observed precisely near the yield point. With further loading until the ultimate strength σ_u is reached, the content of α-martensite is 50%. A similar effect is observed for fatigue loading conditions. First, due to the TRIP effect, with an increase in the maximum cycle stress to 900 MPa, the content of α′-martensite increases from 43 to 68%, and an increase near the fatigue limit from 48 to 68%. With a further increase in the cycle stress to 1300 MPa, the content of α′-martensite slightly decreases. The values of hardness behave very similarly.

It would seem that when we take into account only the TRIP effect, the increase in the content of α′-martensite should continue under loading above the yield point and fatigue limit. However, with an
increase in the stress level, the local area of the deformed material is heated, leading to the reverse martensitic transformation $\alpha' \rightarrow \gamma$, which leads to a certain decrease in the content of $\alpha$-martensite. Previously, a similar effect was observed upon deformation of steel microalloyed with niobium [15].

4. Conclusion
In this work, aspects of the behavior of the alloy under static (at different rates of load application) and cyclic loading (in varying the level of maximum cycle stress) were studied. Statistics gathered during the tests showed that the optimal ratio of $\gamma$-austenite and $\alpha'$-deformation martensite is 1:1. At this ratio, the optimal amount of austenite remains, from which the deformation martensite is formed under the influence of load.

1. The investigated austenitic-martensitic thin-sheet TRIP steel 23Kh15N5AM3-Sh contains 57% $\gamma$-austenite and 43% $\alpha$-deformation martensite and has a good combination of strength and plastic characteristics. In the curve of static tension, until reaching the yield point, a clearly pronounced stage of microyield was found, at which the plastic deformation is $\varepsilon \approx 1\%$. The steel has a very extended yield area with $\varepsilon_y \approx 8\%$. An increase in the tensile rate by a factor of 10 led to a decrease in the values of the ultimate strength by $\approx 6\%$ and the value of the relative elongation $\delta$ from 32% to 21%, due to a decrease in the intensity of the formation of deformation martensite.

2. The nature of hardening during deformation of steel 23Kh15N5AM3-Sh under conditions of static and repeated tension is very similar. For the investigated steel, the effect of the greatest TRIP - hardening took place under loading to the level of stress of the yield point and physical fatigue limit. Then the content of $\alpha'$-deformation martensite decreases due to the occurrence of the reverse martensitic transformation $\alpha' \rightarrow \gamma$ due to the heating of the local deformation region.

3. Preliminary fatigue loading of 23Kh15N5AM3-Sh steel specimens to the fatigue limit does not lead to noticeable changes in static tension. Under fatigue loading up to $\sigma_{max} = 1550$ MPa and $N = 3000$, the values of the yield point and ultimate strength for pre-loaded steel specimens approached and increased by $\approx 200$ MPa and $\approx 100$ MPa, respectively, and the relative elongation decreased by a factor of 2.

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