Effect of Thermo-Mechanical Treatment on the Phase Composition and Resistance to Plastic Deformation of Chromium-Nickel Steel

L. V. Zaitseva
Centre for Technical Inspections Techdiagaz Affiliated Company
Ukrtransgaz National Joint-Stock Company
Naftogaz of Ukraine
56 Volynska st., 03151 Kyiv, Ukraine
E-mail: LZaitseva@tdg.kiev.ua

Boris I. Koval'chuk

National Technical University of Ukraine "Kyiv Polytechnical Institute"
37 Peremogy Prospect, UA-03056, Kyiv-56, Ukraine
E-mail: mef@users.ntu-kpi.kiev.ua

Abstract: The experimental investigation of the influence of time-dependent, thermal and mechanical factors on the kinetics of martensite transformation has been performed in the austenitic chromium-nickel steels. Additionally, the effects of martensite transformation on the mechanical properties are studied and the nature of strengthening is analyzed during low-temperature deformation in the linear and two-dimensional stress states. The equation is evaluated which describes the kinetics of martensitic transformation in the stress strain states. A variant of the deformation theory of plasticity for metastable materials under proportional loading is considered.

Keywords: metastable austenitic steels; plastic deformation; tensile; torsion; compression; biaxial tension; low temperatures; phase $(\gamma \to \alpha)$ *-transformations; plasticity theory*

---

1 Introduction

It is well known [1-3] that processes of phase transformations during plastic deformation in metastable austenitic steels depend essentially on temperature and force loads. The variation of either temperature or force load or their combined change can regulate the intensity of phase transformations and, hence, control the physical and mechanical properties of steels.

This paper presents the experimental results of the comprehensive structural and mechanical studies of 18-10 chromium-nickel austenitic steels. The influence of chemical composition, the mode of refrigeration and storage at low temperatures, the levels of prior plastic deformation on phase compositions and the mechanical properties were analyzed in the steels.

2 Materials, Treatment and Testing

Investigations were carried out using solid (∅ 6 mm) and thin-walled tubular (external diameter 26 mm, wall thickness 0.5 mm) samples. The samples were annealed in vacuum at 1350 K.

The chemical composition of the chromium-nickel steel Cr18Ni10Ti, according to the requirements provided by the GOST, is the following in wt. %: 0,07-0,12 C; 17,0-19,0 Cr; 9,0-11,0 Ni; 1,03 Mn; 0,67-0,41 Ti; 0,39-043 Si; 0,11 Mo; 0,06 V; 0,04 Cu; balance Fe.

The samples were cooled in liquid nitrogen or its vapors.

The phase compositions of steel after the different stages of deformation were determined by X-ray diffraction (XRD) analysis using a DRON-2.0 unit after unloading and reheating to room temperature.

3 Results and Discussion

The intensity of phase transformations under mechanical loading depends significantly on the chemical composition of the steel.

The analysis of the mechanical properties and kinetics of phase transformations of 18-10 type steels under uniaxial tension has demonstrated that a variation of chemical composition within the specified standard limits influences the stability of the structure and, respectively, the steels' mechanical behaviors at low temperatures. A decrease in the test temperature to 77 K results in various changes of strain hardening of the materials. The more unstable steels show their high strain hardening behaviors.

For the purpose of studying the influence of cooling on martensite formation, the samples were tested in the non-deformed and cold deformed (at room temperature) states [4]. One batch of samples was subjected to different numbers of the thermo-cycle: cooling to 77 K, holding for 2-3 min and reheating to 293 K. The second batch was kept in liquid nitrogen for a long time (up to 250 hours). The results of XRD have shown that the volume fraction of martensite f_M increases with an increase in both the number of cycles and the holding time in the liquid nitrogen.

However, the dominant factor contributing to the formation of martensite in material is cooling compared to holding in the refrigerant.

Preliminary deformation by tension in 20% and the long-time recovery of samples at room temperature (for 2-3 months) initiates the different amounts of martensite formation during their subsequent thermal cycling. For instance, the pre-deformed and non-deformed samples have the volume fractions of martensite about 13 and 9%, respectively, after 7 cycles.

The holding of materials under stress at low temperatures results in the formation of an additional amount of martensite. In this case, under holding for 2 hours in the elastic range, the amount of martensite is negligibly small (f_M ~4%), and under holding in the plastic condition, the amount of martensite is high (f_M ~11%).

The major factor affecting the phase composition of metastable austenitic steels is low-temperature plastic deformation. However, the stress state under which deformation is performed is important.

Studies on the influence of stress states on the kinetics of phase transformations during tensile, torsion and compression tests were performed at 77 K. Biaxial tensile tests of thin-walled tubular samples were carried out at the different ratios of principal stresses at temperature 173 K. It was established that the intensity formation of α -phase under tension tests is essentially higher than during torsion and compression experiments.

A study of the structural changes in the material under biaxial tension has indicated that the amount of martensite decreases at the same value of deformation compared to the uniaxial tests, though the resistance of the steel expressed by stress intensity σ_i increases essentially. This behavior is connected with the formation of a stronger martensite under biaxial tension in comparison to uniaxial.

The analysis of the obtained results has shown that the volume content of martensite f_M formed under deformation of austenitic steels depends on the stress deviator (Lode-Nadai parameter $\mu_\sigma = (2\sigma_2 - \sigma_1 - \sigma_3)/(\sigma_1 - \sigma_3)$) and on the rigidity of a stress state, which is characterized by the parameter $k_\sigma = \sigma_0 / \sigma_i$, where $\sigma_0 = (1/3)(\sigma_1 + \sigma_2 + \sigma_3)$ is the mean stress. With an increase in the stress-state rigidity and a decrease in the parameter μ_σ, the process of martensite formation becomes more intensive.

The relation $f_i\ (\varepsilon_i, \mu_\sigma, k_\sigma)$ is complex in nature. Based on the analysis of the surfaces $f_M(\mu_\sigma, k_\sigma)$ which correspond to the different constant values ε_i, a function describing the kinetics of martensite formation under loading was evaluated along arbitrary ray trajectories in three-dimensional stress space:

$$f_M(\varepsilon_i, \mu_\sigma, k_\sigma) = f_0(\varepsilon_i) - c_0(\varepsilon_i)\mu_\sigma + g(\varepsilon_i)(1 + \mu_\sigma) th k_\sigma \tag{1}$$

The functions $f_0(\varepsilon_i)$, $c_0(\varepsilon_i)$ and $g(\varepsilon_i)$ are determined from tensile, compression, and biaxial tension or torsion tests, respectively.

The surfaces $f_M(\mu_\sigma, k_\sigma)$, constructed according to Eq. (l) for some ε_i=const, are shown in Fig. 1. As is seen in Fig. 1, Eq. (1) adequately describes the effect of a stress state on martensitic transformations in 18-10 steels during plastic deformation under combined stress conditions.

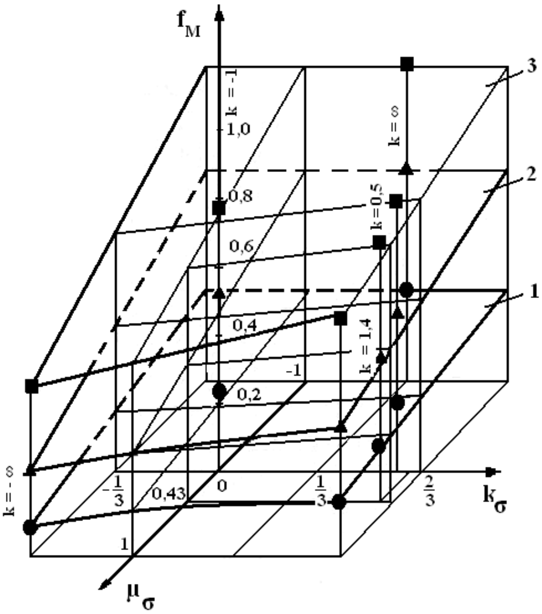


Figure 1

Martensite content f_M vs μ_σ, and κ_σ for fixed strain intensities: $\varepsilon_i = 5\%$ (1, •), $\varepsilon_i = 10\%$ (2, ▲) and $\varepsilon_i = 15\%$ (3, ■). (Surfaces 1-3 are constructed by Eq. (1); points correspond to experimental data.)

Investigations of the loading prehistory on the kinetics of martensite transformations in austenitic steel under repeated plastic deformation, at different preliminary and repeated loadings, temperatures and stress states were performed in [5].

The comprehensive information about the influence of the preliminary thermo-mechanical treatments on plastic deformation and creep behaviours of metals is available in ref. [6-9].

The mechanical tests were performed by six (I—VI) programs according to which the prior and subsequent loadings were carried out by tension and torsion in the different combinations at the temperatures 77 K and 293 K (Table 1). The amounts of plastic pre-strain were reached about 17-30%.

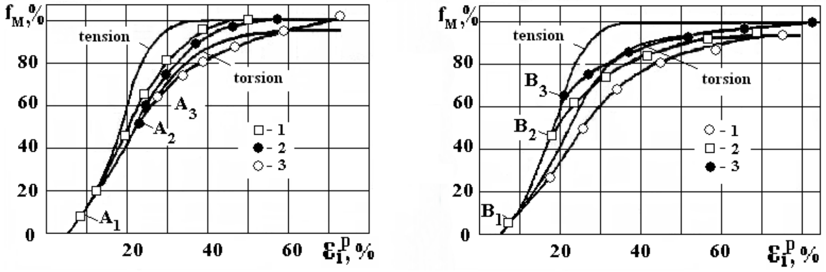
Table 1

Mechanical Test Programs

Program	Prior loading			Repeated loading	
	Form	ε^{p}_{ipr} , %	T_1,K	Form	T_2,K
I	Torsion	8,7 22,9 28,2	77	Tension	77
II	Tension	6,7 17,5 20,1	77	Torsion	77
III	Tension	11,3 18,3 23,9	293	Tension	77
IV	Torsion	19,4 30,4 50,9	293	Tension	77
V	Tension	9,5 17,7	77	Tension	293
VI	Torsion	10,7 7,5	77	Tension	293

The steel investigated was comparatively stable, since its deformation at room temperature did not initiate $(\gamma \to \alpha)$ -transformation up to the failure.

The analysis of the test results under tension after torsion and vice versa (programs I and II) at the same temperature 77 K of preliminary and repeated loadings indicates that a change of a stress state at a low temperature slows down the martensite formation in the steel (Fig. 2).



a *b*

Figure 2

Kinetics of martensitic transformation in chromium-nickel steel at 77 K:

a) program I,1) ε^{p}_{ipr} = 8,7%(A_1); 2) ε^{p}_{ipr} = 22,9%(A_2); 3) ε^{p}_{ipr} = 28,2% (A_3);

b) program II, 1) ε^{p}_{ipr} = 6,7%(B_1); 2) ε^{p}_{ipr} = 17,5%(B_2);) ε^{p}_{ipr} = 20,1% (B_3)

Apparently this result can be explained by the specific nature of martensite transformation. Since $(\gamma \to \alpha)$-transformation is accomplished by shear during plastic deformation, the preferred orientation of a high density of martensite plates in one direction forms due to the slip lines in one direction in the structure. Similar structures have also been observed with deformation of specimens of steel Cr18Ni9 in the temperature range 100-150 K. The development of transverse slip in these grains is difficult because the transverse slip must intersect a slip band of dense bundles of shear lines and martensite plates which exhibit lower ductility and higher yield stresses compared with austenite. Consequently, the formation of a network of directed plates of martensite during prior deformation limits slip in retained austenite under other forms of stressed states. As a result, there is inhibition of martensite transformation at the beginning of deformation, which localizes intensive plastic deformation along slip planes.

The tests at the different stressed states and temperatures (Programs III and IV) indicate that prior loading by both tension and torsion to strain of about 30% at room temperature has little effect on the kinetics of martensite transformation during subsequent low-temperature tension.

At the same time, the prior low-temperature deformation by tension and torsion (Programs V and VI) initiates martensitic transformation during subsequent loading in tension under room temperature conditions (Fig. 3).

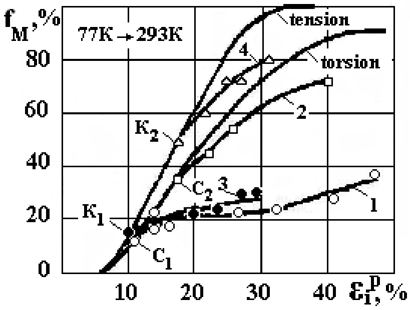


Figure 3
Effect of prior low-temperature deformation for steel by programs
V: 1) ε^p_{ipr} =10,7% (C_1), 2) ε^p_{ipr} =17,5% (C_2), and VI: 3) ε^p_{ipr} =9,5% (K_1), 4) ε^p_{ipr} =17,7%(K_2)

The prior deformation at the low-temperature condition (77 K) initiates the formation of α - phase with repeated "warm" (293 K) loading. The tension of 10% at room temperature after prior low-temperature tension to ε^p_{ipr} =9.5% increases the volume content of martensite to 9%, but after tension up to ε^p_{ipr} =17.7% the amount of martensite is about 2.6%.

Similar results were confirmed by tests of the thin-walled tubular samples under biaxial tension. A preliminary axial tension up to 10% was carried out at temperatures of 77, 123, and 293 K. Repeated loadings were performed at the different ratios of principal stresses and temperatures 123 K and 293 K. In these experiences, strain curves of the steel are recorded in longitudinal and tangential directions that allow measuring the character of the strain hardening and the evolution of the yield surface of steel in the process of plastic deformation.

The results have demonstrated that during plastic deformation of metastable austenitic steel at different temperatures, the direction of maximum hardening in space of stresses may be different from the direction of the preloading. This effect is especially pronounced when the temperatures of preliminary and repeated loading are different and the material is in a metastable state at one of the indicated temperatures. This leads to the complicated transformation of the yield surface that cannot be described by the well-known models of hardening that are usually used in flow theory.

The analysis of the mechanical behavior of metastable steel under plane stress conditions at proportional loading allows for the checking of the basic hypotheses of the strain theory of plasticity. In particular, it was found that the strain curves $\sigma_i = f(\varepsilon_i)$ of steels, obtained during tests of tubular specimens, are non invariant to the stress state (Fig. 4) under plastic deformation. A significant residual change of the steel volume was observed. However, the condition of a similarity of stress and strain deviators is implemented.

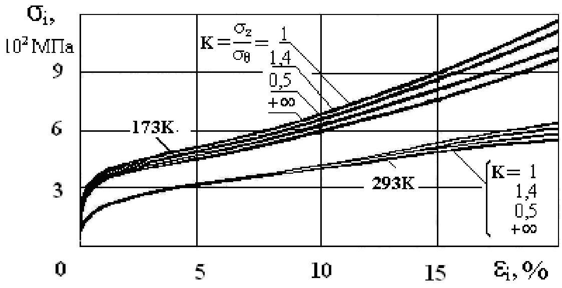


Figure 4

Deformation curves for Cr18Ni10Ti steels at different temperatures under biaxial tension

Based on the formulation of new principles that take into account the influence of the phase transformations on mechanical properties, the constitutive equations of the strain theory of plasticity were deduced. It was applied to metastable materials with deformational phase $(\gamma \to \alpha)$ - transformations in the following form [10, 11]

$$\varepsilon_{ij} = \frac{3}{2}\frac{\varepsilon_i}{\sigma_i(\varepsilon_i, \mu_\sigma, k_\sigma)}(\sigma_{ij} - \delta_{ij}\sigma_0) + \delta_{ij}\left[\frac{\sigma_0}{3K_0} + \varepsilon_f\ (\varepsilon_i, \mu_\sigma, k_\sigma)\right], \tag{2}$$

where K_0 is the volumetric modulus of elasticity, ε_f is the mean residual strain, and δ_{ij} is the Kronecker deltas.

The results of comprehensive mechanical and structural studies of the 18-10 steels made it possible to specify the functions of hardening $\sigma_i(\varepsilon_i,\mu_\sigma,k_\sigma)$ and the residual change of the volume $\varepsilon_i(\varepsilon_i,\mu_\sigma,k_\sigma)$, and they are presented as:

$$\sigma_i(\varepsilon_i,\mu_\sigma,k_\sigma)=\sigma_p(\varepsilon_i)\sqrt{\frac{\mu_\sigma{}^2+3}{(\mu_\sigma+1)^2-2\chi(\varepsilon_i)(\mu_\sigma+1)+4}}\times$$
$$\times\left[1+\psi(\varepsilon_i,\mu_\sigma,k_\sigma)\right]-\sigma_a(\varepsilon_i)\psi(\varepsilon_i,\mu_\sigma,k_\sigma), \tag{3}$$

where

$$\psi(\varepsilon_i,\mu_\sigma,k_\sigma)=\frac{\eta(\varepsilon_i)(1+\mu_\sigma)}{\varepsilon_f^0(\varepsilon_i)-\lambda(\varepsilon_i)\mu_\sigma}\operatorname{th}k_\sigma \tag{4}$$

$$\varepsilon_f(\varepsilon_i,\mu_\sigma,k_\sigma)=\varepsilon_f^0(\varepsilon_i)-\lambda(\varepsilon_i)\mu_\sigma+\eta(\varepsilon_i)(1+\mu_\sigma)\operatorname{th}k_\sigma \tag{5}$$

The functions $\sigma_p(\varepsilon_i)$, $\sigma_a(\varepsilon_i)$, $\chi(\varepsilon_i)$, $\eta(\varepsilon_i)$, $\varepsilon_f^0(\varepsilon_i)$, $\lambda(\varepsilon_i)$ are calculated from the results of the three base experiments, for example, uniaxial tension, uniaxial compression and biaxial tension at σ_2/σ_1=0,5 or torsion.

The calculation results obtained by Eqs. (2), (3), (4) and (5) are in a good agreement with experimental data for proportional loading of 18-10 steels in a metastable state.

Conclusions

The thermal cycling of the metastable stainless steels initiates phase transformations leading to some increase in their strength. The external load and the thermal stresses contribute to these processes.

The type of stress state has a significant effect on the kinetics of martensitic transformations and the stress-hardening of steels. There is no unique dependence between the amount of martensite formed and the resistance of steel, since the strength of martensite depends on the type of stress state.

Preliminary plastic deformation of steels at room temperature has no significant influence on their mechanical properties at low temperatures. At the same time, a preliminary low-temperature deformation initiates phase transitions and improves the mechanical properties of steels at room temperature. The discrepancy between the forms of stress states in the preliminary and subsequent deformation slows down the phase transformations in steel Cr18Ni10Ti.

The mathematical model describing the kinetics of martensitic transformations in steels during plastic deformation under complex stress states as well as the plastic deformation of unstable structure under proportional loading are considered.

References

[1] M. Smagaa, F. Walther, A, D. Eiflera.: Deformation-Induced Martensitic Transformation in Metastable Austenitic Steels, *Materials Science and Engineering: A* Vol. 483-484, pp. 394-397, 15 June 2008

[2] Noriyuki Tsuchida, Kenzo Fukaura, Yo Tomota, Atsushi Moriai, Hiroshi Suzuki: Tensile Deformation Behaviors of Metastable Austenitic Stainless Steels Studied by Neutron Diffraction, *J. Materials Science Foru,* Vol. 652, pp. 233-237, 2010

[3] Tetsu Narutani: Effect of Deformation-Induced Martensitic Transformation on the Plastic Behavior of Metastable Austenitic Stainless Steel, *Materials Transactions*, JIM, Vol. 30, No. 1, pp. 33-45, 1989

[4] Lebedev A. A., Koval’chuk B. I., Zaitseva L. V.: Effect of Thermomechanical Conditions on the Kinetics of Phase Transformations in Austenitic Metastable Steel, *J. Strength of Materials*, Vol. **27**, No. **3**: pp. 124-128, 1995

[5] Koval'chuk B. I., Zaitseva L. V., Lebedev A. A., Kosarchuk V. V.: Effect of Loading Prehistory on Phase Transformations in Chromium-Nickel Steel with Plastic Deformation, *J. Strength of Materials*, Vol. **10:** pp. 1101-1105, 1991

[6] Rusynko A. Influence of Preliminary Mechanical and Thermal Treatment on the Steady-State Creep of Metals, *J. Materials Science* **40**: 223-231, 2004

[7] Ruszinko, E. The Influence of Preliminary Mechanical-thermal Treatment on the Plastic and Creep Deformation of Turbine Disks, *J. Meccanica* **44**: 13-25, 2009

[8] Rusinko, A., Rusinko, K. Synthetic Theory of Irreversible Deformation in the Context of Fundamental Bases of Plasticity, *Int. J. Mech. Mater.* **41**: 106-120, 2009

[9] Rusinko A. Non-Classical Problems of Irreversible Deformation in Terms of the Synthetic Theory, Acta Polytechnica Hungarica Vol. 7, No. 3, pp. 25-62, 2010

[10] Koval’chuk B. I., Zaitseva L. V.: Derivation of the Stress-Strain Equations for Metastable Materials with Martensite Transformations under Proportional Loading, *J. Strength of Materials*, Vol. **31**, No **3**, pp. 232-240, 1999

[11] Lebedev A. A., Koval’chuk B. I., Zaitseva L. V.: Deformation of Structure-Unstable Medias under Combined Stress Conditions and his Mathematical Design, *Vestnik of the KPI Nat.Techn.Univ.*, ser. Engineering, VIPOL Publ., **52**: pp. 78-88, 2008