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Kinetic Plasticity during Quenching of Chromium Steel

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In this work we study the mechanical behavior of high chromium and medium chromium steels during quenching. The microstructure of such a steel contained different quantities of retained austenite, which transformed to martensite during subsequent straining resulting in both high strength and toughness of steel. During mechanical loading, the austenite undergoes a displacive phase change and transforms into martensite. This transformation is accommodated by plastic deformations in the surrounding matrix. Test results of kinetic plasticity of steel with different quantities of alloying elements, especially of chromium, are presented in this work. Behavior of steel during martensitic transformation depends on internal and external factors: on chemical composition of steel and heating temperature. Hardening at optimal temperature steels with chromium content from 0.99 % until 18.20 % show maximum rate of relative rate of transformation plasticity. This phenomenon can be used for renovation and restoration of the details and the components deformed during exploitation, and for production of steels with high formability.

Keywords: high chromium, deflection, quenching, kinetic plasticity.

1. INTRODUCTION

Due to the strain-induced martensitic transformation, the strength, ductility and toughness of steel are enhanced. Steel possesses such favorable macroscopic mechanical properties as a result of the appropriate combination between this behavior and the deformation behaviors of the austenitic and martensitic phases at a scale of crystal grain [1]. Recently, a texture evolution by martensitic transformation is being focused on and it is possible that the control of such favorable mechanical properties of steels will be realized by the control of the texture evolution by strain-induced martensitic transformation. Therefore, not only the appropriate constitutive model at the scale of a single crystal but also a suitable model for a formation of a microstructure are necessary to predict this transformation texture evolution. Here, the constitutive equation for a single crystal steel including transformation strain on each variant is formulated based on the continuum crystal plasticity theory. Then, the deformation behavior with patterning process of martensitic phase is simulated under plane strain condition by introducing formulated constitutive equation to FEM with cellular automata approach.

Transformation induced plasticity (TRIP) effect is used for production of steels with high strength and high formability. The remarkable strength to ductility balance results form strain-induced transformation of retained austenite to martensite during plastic deformation [2].

The transformation of austenite to martensite is fundamental to the hardening of carbon steels. This transformation plays an important role for the mechanical behavior of low-carbon ferrous alloys containing about 10 vol. % retained austenite. Results show [3] that a homogeneous microstructure and the absence of initial blocky martensite ensure long deformation paths. At the same time, tensile data reveal only a small influence of deformation parameters on the ultimate strength.

Other authors suggested a microstructure-based computational model, which can describe the transformation induced plasticity accompanying the mechanically induced martensitic transformation in metastable austenitic steel. The martensitic transformation kinetics was assumed as a nucleation-controlled phenomenon. The probability, which the nucleation site would really act, was derived for each martensitic variant as a function of the interaction energy between externally applied stress state and lattice deformation. The increase of nucleation site in the austenite due to the plastic deformation was formulated as the increase of the shear-band intersection.

Stress-induced martensitic transformation in Fe-Mn-Si alloys [4] is characterized by the transformation of the fcc matrix to the hcp phase, which is generally reversible. In this study, Debye rings obtained by monochromated X-ray diffraction using synchrotron radiation were used for analyzing the structural change of the fcc matrix to the hcp phase in a polycrystalline austenitic Fe-Mn-Si-Cr alloy that was deformed by the tensile test at room temperature. Structural changes resulting from the reverse transformation due to heating were also studied. The results showed that the occurrence of the stress-induced martensitic transformation was not uniform, but depended on the relationship between the orientation of polycrystalline grains and the tensile direction. The transformation appears to preferentially occur in grains with large Schmid factors for the shear of [\bar211](111) in the fcc matrix, and the formation of hcp phases also depends on the orientation of grains. The reverse transformation due to heating does not necessarily occur in the crystallographically reversible route. This indicates that irreversible deformation induced by dislocations during the tensile test restricts the reversible transformation of the alloy.

The strain-induced martensitic transformation, however, strongly depends on the temperature and strain rate

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imposed, and an appropriate improvement of mechanical properties is realized under quite restricted circumstances. To obtain the required mechanical properties, a constitutive model, which can suitably predict the deformation behavior including transformation under a wide range of deformation rate and temperature, has been developed by employing Olson and Cohen's model for strain-induced martensitic transformation kinetics [5]. The possibility of the improvement of such mechanical properties of material as strength, ductility and toughness has been individually discussed [6].

Experimental results show that the presence of austenite typically enhances the ductility and strength of steel [7]. They use a recently developed model to analyze in detail the contribution of the martensitic transformation to the overall stress-strain response of a specimen containing a single island of austenite embedded in a ferrite-based matrix. Results show that the performance of the material depends strongly on the lattice orientation of the austenite with respect to the loading direction.

In the present work we study transformation plasticity, abnormality of steel plasticity during martensitic transformation. The main purpose of this work is to investigate kinetics of the transformation plasticity behavior. Other targets are to determine relations between magnitude of normal bending stresses and plastic deformation of test pieces, to examine influence of hardening temperature on the kinetic plasticity, to calculate modulus of transformation plasticity E_{tp}.

2. EXPERIMENTAL

The tests of kinetic plasticity were accomplished on bended test pieces. Both loaded and unloaded test pieces show creep phenomena. When stresses do not exceed limit of elasticity, than remaining deformation is equal to zero. Significant remaining deformation can be observed then elastic-plastic strains are composed. Creep phenomena can be observed: at ambient temperature then strains are huge and loading time is long enough; at the temperature exceeding 300 °C; then steel is in a condition of superplasticity (structural superplasticity, transformation and kinetic superplasticity). In a condition of kinetic plasticity creep of steel is huge (it exceeds creep values in an austenitic condition), so in a short interval of time it is possible to accumulate huge plastic deformation.

Heated up to the hardening temperature test pieces were placed into the special device and were loaded and bent by magnitude y_{ep} (Fig. 1). This deflection of austenitic condition is elastic or elastic-plastic, what's why displays creep of test pieces and its deflection increases slightly. When cooling, strength of steel increases, so plastic deformation due to creep dying-out. When temperature of test piece reaches temperature of beginning of martensitic transformation M_S and when martensitic transformation begins, test piece intensively plastically deforms.

Shape of plastic deflection curve similar to curve of martensite transformation in Time-Transformation-Temperature (TTT) diagram. It shows relation between transformation plasticity and martensitic transformation. When the test piece reaches the ambient temperature deflection process stops. On unloading deflection of test piece drops by magnitude of elastic deflection y_e. The load makes remaining deflection y_m. Deflection size in this curve qualitatively shows increment of steel plasticity during martensitic transformation. Quantitative evaluation can be attained after calculation of kinetic plasticity modulus M^G_{KP}, using magnitudes y_t and y_e assessed during experiments.

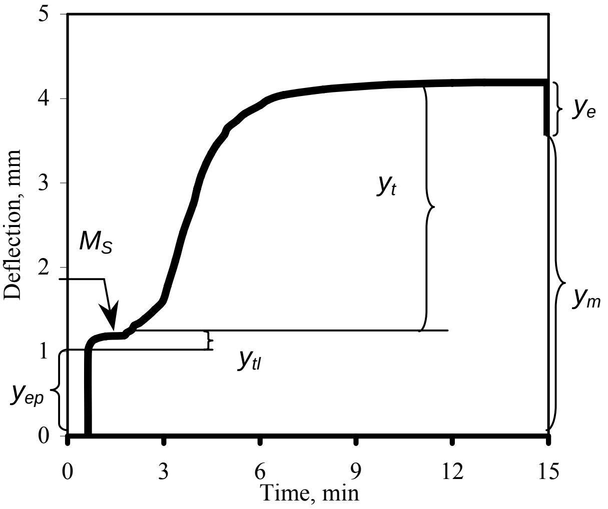

Fig. 1. Kinetics of the test piece deflection during martensitic transformation. Steel with 18.20 % of Cr (Table 1). Hardening temperature 1050 °C, cooling in the air, normal bending stresses 300 MPa: y_{ep} – elastic plastic deflection; y_{tl} – alternation of deflection due to creep; y_t – alternation of deflection due to kinetic plasticity; y_e – elastic alternation of deflection when unload; y_m – remaining deflection

Alloyed steel with different amounts of carbon content from 0.12 % to 1.60 % and different amount of chromium content from 0.99 % to 18.20 % were chosen for the experiments. Chemical composition of steel (grade according to Russian standard GOST) is given in the Table 1.

Table 1. Chemical composition of alloys

Steel grade*	Alloying elements, %				
	C	Cr	Mn	Si	Ni
40X13	0.38	12.89	0.35	0.32	0.30
95X18	0.97	18.2	0.55	0.55	0.39
X12Ф1	1.25–1.45	11.0–12.5	0.15–0.40	0.15–0.35	–
	Other elements (%) V – 0.70-0.90				
P6M5	0.83	3.88	–	0.22	2.9
	Other elements (%) V – 1.30; Mo – 4.64; W – 5.82				
XBГ	0.99	0.99	0.90	0.30	
	Other elements (%) W – 1.40				

* Steel grades according to Russian standard GOST.

Chemical composition of steel has great influence to progress of martensitic transformation. Alloying elements increase activation energy of martensitic transformation, extended incubation period and lowered rate of transformation. Temperatures of beginning and end of martensitic transformations strongly depend on low carbon content in the steel. If carbon content increases, temperatures of martensitic transformation (beginning and end) decreases.

After hardening wide range of chemical composition was observed: quantity of retained austenite from 0 % to 98 %, quantity of carbide phase from 0 % to 30 %. Other authors [3] investigated steel with 10 % of retained austenite, but we found that deformation paths have the same trajectory, just intensity differ. Such a wide variety of physical and chemical composition selected for our investigations enables to investigate plasticity of steel deformation during heat treatment and after it. The chosen steel grades have stabile austenite, therefore it is possible to make all necessary test of kinetic plasticity during quenching in the oil or air. Moreover these steels are widely used in the practice.

Steel with 12.89 % of chromium (40X13) – stainless chromium steel used for springs, machine components and tools, susceptible for secondary hardness during subsequent tempering. Steel with 18.20 % of Cr (95X18) – high alloyed steel with low plasticity, corrosion and abrasion resistant, used for making rolling bearings. Steel with 12 % of Cr (X12Ф1) – high abrasion resistant ledeburitic steels used for making of cold working dies and some cutting tools. Steel with 3.88 % of Cr (P6M5) – high speed ledeburitic steel. Steel with 0.99 % of Cr (XВГ) – tool steel used for making of cutting tools. Test pieces were prepared from hot rolled bars.

All magnitudes calculated for steels with 12.89 % and 18.20 % are presented in Table 2 and Table 3.

Table 2. Modulus of kinetic plasticity M^G_{KP} of steel with 12.89 % of Cr as a result of load

σ_l	y_{ep}	y_t	y_e	A_m[1]	M^G_{KP}	$K_p = \frac{E}{M^G_{KP}}$ [2]
MPa	mm	mm	mm	%	MPa	
70	0.20	0.79	0.07	22.9	18793	11.60
100	0.38	1.09	0.11	24.1	19963	10.92
150	0.55	1.64	0.16	25.3	18350	11.88
200	0.82	2.18	0.22	19.5	19782	11.02
250	1.10	2.84	0.27	18.6	18956	11.50

[1] Quantity of retained austenite;
[2] Relative rate of kinetic plasticity;
Hardening temperature 1050 °C.

Table 3. Modulus of kinetic plasticity M^G_{KP} of steel with 18.20 % of Cr as a result of load

σ_l	y_{ep}	y_t	y_e	A_m[1]	M^G_{KP}	$K_p = \frac{E}{M^G_{KP}}$ [2]
MPa	mm	mm	mm	%	Mpa	
70	0.17	0.81	0.07	35.6	18514	11.80
100	0.22	1.12	0.11	29.7	19464	11.20
150	0.30	1.52	0.16	35.6	20782	10.49
200	0.45	2.08	0.22	30.2	20821	10.47
250	0.70	2.39	0.27	37.1	22474	9.70
300	0.82	2.93	0.31		20861	10.45
400	1.25	4.01	0.44		21584	10.10

[1] Quantity of retained austenite;
[2] Relative rate of kinetic plasticity;
Hardening temperature 1050 °C

3. INFLUENCE OF CHEMICAL COMPOSITION ON KINETIC PLASTICITY

In the works of other researchers transformation induced plasticity effect is solved in a sense of structural phase transformations [4], using models, which can predict steel behavior [5]. One of the targets of our research was to analyze influence of chemical composition. The composition of austenite influences on mechanical properties of the phase and on thermal stability during quenching. Materials chosen for the experiments enable to perform this investigation.

High chromium die steel with 12 % of Cr can be hardened in a wide range of hardening temperatures for achieving primary and secondary hardness. Chromium carbides easily dissolve at temperatures higher than 1000 °C, so hardening temperature of these steels was in the temperature range of 950 °C – 1100 °C. Hardening temperatures considerably change kinetics of plasticity alternation and size of plastic deflection (Fig. 2.)

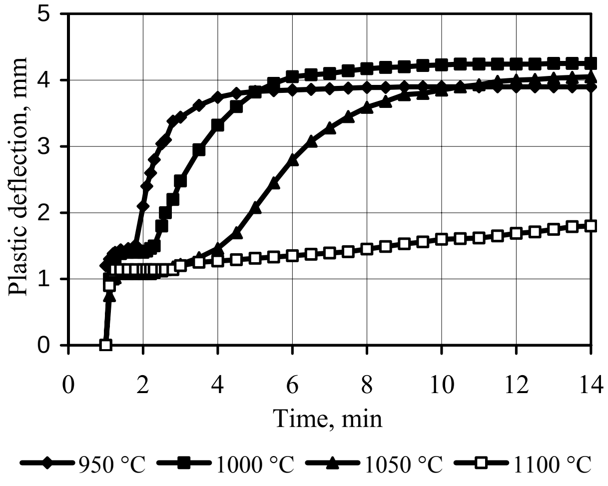

Fig. 2. Kinetics of test pieces, made of steel with 12 % of Cr (X12Ф1), deflection

When hardening temperature 950 °C, temperature of beginning of martensitic transformation $M_S = 300$ °C, test piece bends intensively, but its plastic deflection is slightly lower than the deflection of test pieces hardened at the temperature range 1000 °C – 1050 °C. Raising hardening temperature from 1000 °C to 1050 °C chromium carbide M_7C_3 solves in the matrix, austenite enriches with carbon and chromium and temperature of beginning of martensitic transformation decreases to temperatures 240 °C – 160 °C. Deform at these temperatures test pieces bend slower, because of lower rate of martensitic transformation, but plastic deflection after the experiments is higher than deflection of test pieces hardened at 950 °C. Although in these test pieces quantity of retained austenite was higher (18 % when $T_h = 1000$ °C and 28 % when $T_h = 1050$ °C), rate of martensitic transformation was lower, so plastic deflection should be lower. According to the results of experiments reverse results were obtained: plastic deflection of test pieces hardened at the temperature of 1000 °C higher by 17 %, at the temperature 1050 °C – 31 %. Such a contradictory result can be explained that hardened at the higher temperatures, austenite possess higher quantities of dissolved carbon which increases kinetic plasticity.

Hardening steel with 12 % of Cr at the temperature of 1100 °C plastic deflection was low: just 47 % of transformation deflection comparing with magnitudes obtained hardened at 950 °C. Low rate of martensitic transformation (martensite quantity 20 %) determines such a low plasticity.

The same dependences of kinetic plasticity to hardening temperatures were obtained testing other high chromium steels (12.89 % and 18.20 % of Cr). Test pieces prepared from steel with 12.89 % of Cr, hardened at different temperatures at the beginning bend with different intensity but plastic deflection differ just slightly (0.1 mm – 0.3 mm). Test pieces prepared from steel with 18.20 % of Cr showed different plasticity. Its plastic deflection after hardening at 1050 °C five times higher than plastic deflection of test pieces hardened at 1100 °C. It can be explained that hardened at this temperature comparatively low content of martensite compose.

Relative rate of kinetic plasticity K_P of examined steels are plotted in Fig. 3.

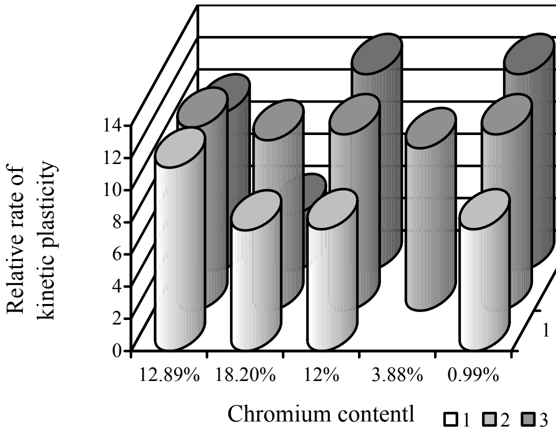

Fig. 3. Dependence of chemical composition on kinetic plasticity. 1 – hardening temperature lower than optimal; 2 – optimal hardening temperature; 3 – hardening temperature higher than optimal

This figure shows that kinetic plasticity of low alloyed steel with 0.99 % of Cr (ХВГ) increases with raising hardening temperature and do not decreases after overheating (temperature 3). Overheating temperature is very important for properties of high chromium stainless steels (12.89 % and 18.20 % of Cr). When overheated these steels, its relative rate of kinetic plasticity decreases because of quantity of retained austenite formed during overheating. Using optimal hardening temperatures for each steel magnitudes of relative rate of kinetic plasticity are similar.

4. CONCLUSIONS

1. During martensitic transformation steel possess kinetic plasticity, which magnitude can be evaluated by modulus of kinetic plasticity M_{KP}^{G} and by relative rate of kinetic plasticity K_P.
2. Size of the kinetic plasticity depends on chemical composition of steel and hardening temperature.
3. When increased normal bending stresses, relative rate of kinetic plasticity of steel with 18.20 % and 3.88 % of chromium decreases.
4. For high carbon steel with lower content of carbon (steel 40X13) size of load does not influence relative rate of kinetic plasticity.
5. Relative rate of the kinetic plasticity of chromium steels (Cr content from 0.99 % until 18.20 %) reaches maximum (~11) when steel is hardened at the optimal hardening temperature.

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