DOI 10.1007/s11015-014-9982-3
Metallurgist, Vol. 58, Nos. 7–8, November, 2014 (Russian Original Nos. 7–8, July–August, 2014)

HEAT TREATMENT TECHNOLOGY FOR HIGH-STRENGTH ENGINEERING STEEL VARIABLE CROSS-SECTION COMPONENTS

**M. V. Maisuradze,[1] M. A. Ryzhkov,[1]
Yu. V. Yudin,[1] and A. A. Ershov[2]**

UDC 669.017

Heat treatment parameters providing a required level of mechanical properties for different component parts are determined on the basis of experimental data about supercooled austenite transformation in engineering chromium-nickel-molybdenum steel, and also results of numerical modeling of variable cross-section components of this steel in a QForm 7 program.
Keywords: *supercooled austenite, thermokinetic diagram, heat treatment, numerical modeling, QForm, mechanical properties, microstructure.*

One of the main tasks in contemporary engineering is provision of a required level of high-strength steel component properties for critical and special purposes with an increase in economic efficiency for their manufacture [1]. Normally economically correct exclusion from a production process of welding and cold or hot upsetting leads to a need to fabricate components with massive and thin parts (for example, shafts for various purposes, reactor components, transmission boxes, etc.) [2–4].

However, in order to obtain prescribed and often different mechanical properties in parts of different cross section comprehensive heat treatment regimes are developed (HT) for a component. They may include both differential treatment of individual parts of a component [5, 6], and different versions of surface hardening (carburization [7, 8], nitriding [9, 10], hardening after surface heating by high-frequency current [11, 12]). These operations require strict observation of production process parameters, since any deviation from a prescribed regime may lead to unremovable defects. In addition, there is an increase in treatment duration. This increases cost and reduces component competitiveness.

Thus, provision of a set of mechanical and operating properties for engineering components of variable cross section with a reduction in material and time expenditure on their production is an important question. This work is devoted to scientifically substantiated selection of the optimum heat treatment for engineering components of variable cross section made of high-strength steel in order to obtain a prescribed level of properties in different parts of a component after low-temperature tempering.

The objects studied were components of variable cross section of cylindrical shape of high-strength engineering steel 25Kh2N4MA of the following chemical composition, wt.%: C 0.24, Cr 1.43, Ni 4.06, Mo 0.32, Mn 0.34, Si 0.28, Cu 0.18, S 0.005, P 0.005. Structural parameters of the component: largest diameter (massive part) 180 mm (length 105 mm), diameter of the smaller (thinnest) part 100 mm (length 250 mm); there is a hole 30 mm in diameter along the component axis.

[1] Ural Federal University (UrFU), Ekaterinburg, Russia; e-mail: spirallog@gmail.com, mt-243@mail.ru.
[2] PLM Ural – Deklam-Ural Company Group, Ekaterinburg, Russia; e-mail: eaa@delcam-ural.ru.

Translated from Metallurg, No. 8, pp. 101–104, August, 2014. Original article submitted August 7, 2014.

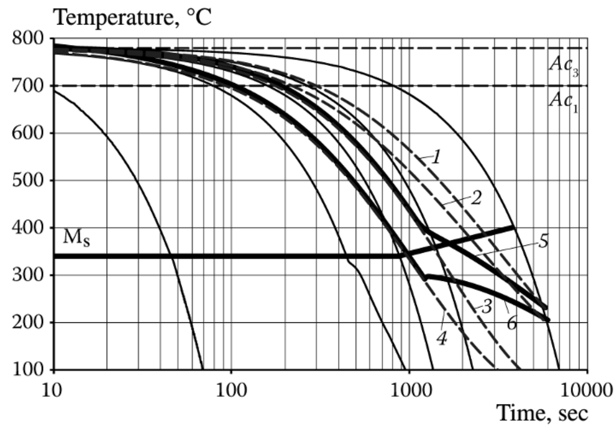


Fig. 1. Thermokinetic diagram of steel 25Kh2N4MA supercooled austenite transformation for cooling from 825°C with calculated cooling trajectories of massive (*1*, *3*, *5*) and thin (*2*, *4*, *6*) component parts: *1*, *2*) cooling in still air; *3*, *4*) accelerated cooling; *5*, *6*) controlled cooling.

In order to determine the temperature and time ranges of the process for transforming supercooled austenite in test steel, studies were performed in a Linseis L78 R.I.T.A. dilatometer. Heating of a specimen 10 mm long and 4.5 mm in diameter was carried out up to 825°C, and the soaking time was 15 min. Specimen cooling was implemented at a constant rate in the range 0.1–30 °C/sec.

Steel Rockwell hardness scale C was determined in accordance with GOST 9013. Mechanical properties with uniaxial tension were determined according to GOST 1497 in an Instron 3380 test machine. Specimens were selected from heat treated components along the rolling direction of original metal. Specimen microstructure was studied by means of an Altami MET 1M interference optical microscope.

Modeling of test component cooling was carried out in a QForm 7 program for several conditions: in still air, in an accelerated air stream, and with changes of cooling intensity (average surrounding heat removal coefficient). The solution was accomplished in a 2D axisymmetrical arrangement with a maximum element size of 1 mm and a maximum step with respect to time of 5 sec. The starting data for calculations used were values of deformation resistance presented on a standard database of the QForm 7 program for steel 20NiCrMo14-16 (DIN 1.6742, Germany), average values of physical properties: thermal conductivity coefficient 31 W/(m·K); specific heat capacity 700 J/(kg·K); density 7850 kg/m^3; Young's modulus 210 GPa; Poisson's ratio 0.3; thermal expansion coefficient $11.65 \cdot 10^{-6}$ K^{-1}. In order to calculate the structures obtained as a result of heat treatment, groups of material were selected according to recommendations for development of software. The average heat output coefficient on cooling a component with an accelerated air stream was assumed to be 87.5 W/(m^2·K), and in still air 12.5 W/(m^2·K) [13].

Experimental results. Dilatometric data obtained with heating at a rate of the order 0.1 °C/sec were used to determine critical temperature values for steel 25Kh2N4MA: Ac_1 = 700°C; Ac_3 = 780°C. Proceeding from this, the austenitizing temperature was selected for the test steel as 825°C. On cooling from 825°C, a thermokinetic diagram (TKD) was plotted for transformation of supercooled austenite in the test steel in the range of constant cooling rates from 0.1 to 30 °C/sec (Fig. 1).

With cooling at a rate of 0.1–0.3 °C/sec, hardness of the test steel was HRC 44–45. With a cooling rate of more than 0.3 °C/sec, the hardness increases to HRC 47 and reaches HRC 50 with a cooling rate of 30 °C/sec, which is connected with an increase in the proportion of martensite within the structure. Temperature for the start of martensitic transformation with test steel cooling from 825°C was 340–350°C.

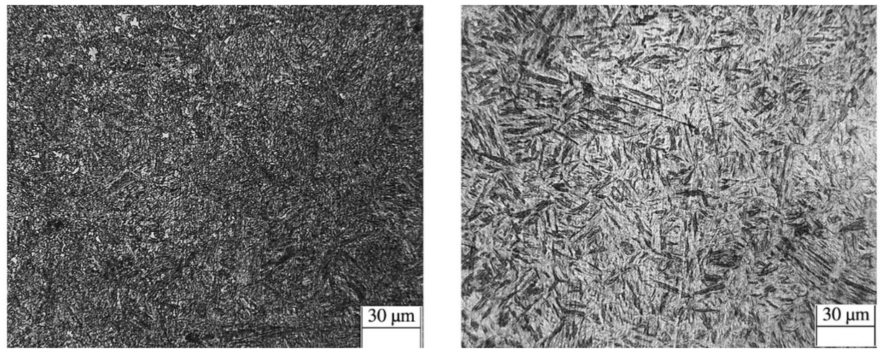
In accordance with operating conditions for the test engineering components, it is necessary to provide a higher strength level in a thin section and increased ductility in a massive section. The required component cooling intensity was calculated in order to achieve this. It was established that cooling in still air makes it impossible to obtain a martensitic structure, and correspondingly, a higher level of hardness and strength in a thin section of a component (cooling trajectories *1* *a*  *b*

Fig. 2. Microstructure of massive (*a*) and thin (*b*) steel 25Kh2N4MA component parts after controlled heat treatment.

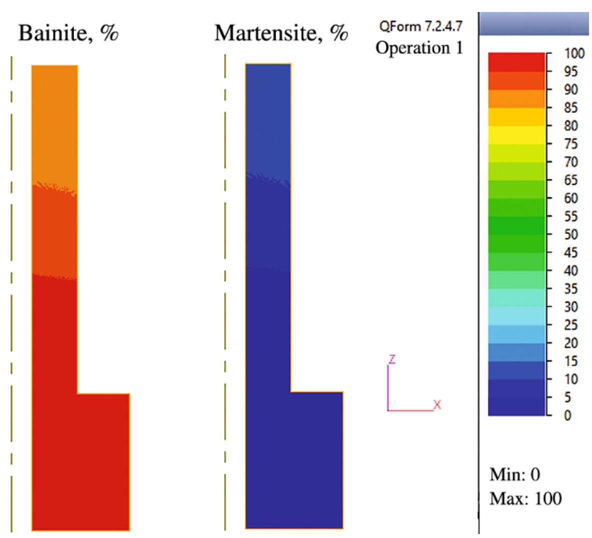


Fig. 3. Calculated structure fields after steel 25Kh2N4MA component controlled heat treatment.

and *2*, see Fig. 1). In this case, it is necessary to perform additional heat treatment with heating by a high frequency current or other methods.

Accelerated cooling facilitates the formation of a predominantly martensitic structure with a small amount of bainite both in thin and massive parts of a component (cooling trajectories *3* and *4*, see Fig. 1). In order to reduce the strength level and increase ductility of the massive part of a component, it is necessary to perform additional local tempering in molten salt or alkali.

The versions of HT considered for components of variable cross section require installation of additional expensive equipment. In addition, time spent in treating components increases, i.e., a reduction in productivity and an increase in the probability of developing scrap as a result of deviations from the designated regimes or equipment breakdown.

In order to resolve these problems, controlled cooling regimes were considered for components: at first in an air stream in order to prepare a martensitic structure in the thin section of a component, and then in still air in order to form a more ductile bainitic structure in the massive part.

The main parameter of this cooling regime is duration of the first stage, i.e., accelerated cooling in an air stream. In order to estimate its duration, modeling was carried out using QForm 7 software. The criterion for the end of accelerated cooling was selection of the instant of achieving an average mass temperature of the order of 400°C in the massive part of a component (cooling trajectory *5*, see Fig. 1). According to dilatometric studies in this temperature range in steel 25Kh2N4MA bainitic transformation commences in the cooling range 0.3–0.5 °C/sec, which is achieved with accelerated cooling in an air stream.

At the same time, the average mass temperature of the thinnest part of a component at the instant of transition to cooling in still air is about 500°C (cooling trajectory *6*, see Fig. 1), which is lower than the temperature for the start of martensitic transformation. With further slow cooling in still air, according to the TKD, in the thin section of a component a structure of martensite and lower bainite should form with increased hardness and strength.

Thus, the required accelerated cooling duration in an air stream was determined for a component of variable cross section, which was of the order of 1200 sec (20 min). The second cooling stage (in still air) continued to complete component cooling down. In this time within the massive part of a component there should be formation of a predominantly bainitic structure.

An experiment was performed under industrial conditions in accordance with which a component of variable cross section of steel 25Kh2N4MA was given HT using controlled cooling by the regime indicated above. After HT, specimens were selected from the thin and massive parts of the component for studying microstructure and mechanical property determination.

Results of metallographic analysis showed that within the structure of the massive part of a component there is predominantly a bainitic structure with a small amount of martensite, experiencing partial self-tempering (Fig. 2*a*). Within the structure of the thin section of a component there is a martensite-bainite structure (Fig. 2*b*). Similar distribution of the microstructure through the cross section of a component has been determined as a result of numerical modeling of HT in the QForm 7 program (Fig. 3). Mechanical properties of different sections of steel 25Kh2N4MA component after controlled cooling are provided below:

	Massive part	Thin part
$\sigma_{0.2}$, MPa	1340 ± 40	1620 ± 40
σ_u, MPa	1470 ± 40	1720 ± 40
δ_5, % R.p.103	16 ± 1	12 ± 1
ψ, %	49 ± 3	43 ± 3
Hardness, HRC	40–42	47–48

Thus, parameters of a controlled cooling regime, determined by means of numerical modeling, provide increased ductility and reduced strength for the massive part of a component of variable cross section, and within the thin part of a component the required higher strength level is provided.

Conclusions

1. As a result of dilatometric study of engineering steel 25Kh2N4MA, critical points have been determined on heating (Ac_1 = 700°C; Ac_3 = 780°C), temperature-time ranges for phase and structural transformations in the range of constant cooling rates 0.1–30 °C/sec. It has been established that bainitic transformation in the test steel is realized with cooling at a rate of less than 0.5 °C/sec. Temperature for the start of martensitic transformation is 340–350°C.

2. On the basis of numerical modeling in a QForm 7 program, parameters have been established for a controlled cooling regime for components with variable cross section of steel 25Kh2N4MA: accelerated cooling duration in an air stream 1200 sec, and subsequent cooling in still air to room temperature.

3. It has been established that the regime developed for controlled cooling made it possible to obtain the required microstructure and mechanical properties for an object cross section. The structure of a massive part of a component of variable cross section consists mainly of bainite with a hardness level of HRC 40–42, σ_u = 1470 MPa, $\sigma_{0.2}$ = 1340 MPa, but within the structure of a thin section of a component there is a mixture of martensite and bainite with a hardness level HRC 47–48, σ_u = 1720 MPa, $\sigma_{0.2}$ = 1620 MPa.

The work was carried out with partial financial support from the UrFU within the scope of a program for developing UrFU for winners of the “Young Scientists of UrFU” competition. Results used in the work were obtained in the TsKP UrFU laboratory of structural analysis methods and nanomaterial properties.

REFERENCES

1. V. N. Nikitin, A. P. Shlyamnev, M. V. Nikitin, and M. N. Pankova, “New approach to the development of high-strength structural steels with ultimate strength of 1350 MPa or more,” *Metallurgist*, 55, No. 3/4, 171–176 (2011).
2. C. Moolwan and S. Netpu, “Failure analysis of a two high gearbox shaft,” *Proc. Soc. Behav. Sci.*, **88**, 154–163 (2013).
3. H. Bayrakceken, “Failure analysis of an automobile differential pinion shaft,” *Eng. Fail. Anal.*, **13**, 1422–1428 (2006).
4. Z. Pang, Sh. Yu, and J. Xu, “Study of effect of quenching deformation influenced by 17CrNiMo6 gear shaft of carburization,” *Phys. Procedia*, **50**, 103–112 (2013).
5. H. R. B. Rad, A. Monshi, M. H. Idris, et al., “Premature failure analysis of forged cold back-up roll in a continuous tandem mill,” *Mat. Design*, **32**, 4376–4384 (2011).
6. M. K. Lee, G. H. Kim, K. H. Kim, and W. W. Kim, “Control of surface hardnesses, hardening depths, and residual stresses of low carbon 12Cr steel by flame hardening,” *Surf. Coat. Technol.*, **184**, 239–246 (2004).
7. T. M. Loganathan, J. Purbolaksono, J. I. Inayat-Hussain, and N. Wahab, “Effects of carburization on expected fatigue life of alloys steel shafts,” *Mat. Design*, **32**, 3544–3547 (2011).
8. A. Sugianto, M. Narazaki, M. Kogawara, et al., “Numerical simulation and experimental verification of carburizing quenching process of SCr420H steel helical gear,” *J. Mater. Proc. Techn.*, **209**, 3597–3609 (2009).
9. N. Limodin and Y. Verreman, “Fatigue strength improvement of a 4140 steel by gas nitriding: Influence of notch severity,” *Mat. Sci. Eng. A*, **435–436,** 460–467 (2006).
10. S. Y. Sirin and E. Kaluc, “Structural surface characterization of ion nitrided AISI 4340 steel,” *Mat. Design*, **36**, 741–747 (2012).
11. Y. Totik, R. Sadeler, H. Altun, and M. Gavgali, “The effects of induction hardening on wear properties of AISI 4140 steel in dry sliding conditions,” *Mat. Design*, **24**, 25–30 (2003).
12. I. Magnabosco, P. Ferro, A. Tiziani, and F. Bonollo, “Induction heat treatment of a ISO C45 steel bar: Experimental and numerical analysis,” *Comput. Mat. Sci*., 35, 98–106 (2006.).
13. J. R. Welty, C. E. Wicks, R. E. Wilson, and G. L. Rorrer, *Fundamentals of Momentum, Heat and Mass Transfer*, John Wiley & Sons, NY USA (2008), 5th ed.