A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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NEW HIGH HARDNESS Mn-Cr-Mo-V TOOL STEEL

NOWA STAL NARZĘDZIOWA Mn-Cr-Mo-V O WIELKIEJ TWARDOŚCI

The article presents results of the study on mechanical properties of a new hypereutectoid Mn-Cr-Mo-V steel. Mechanical tests comprised tensile test, impact toughness test and hardness measurements. Moreover, the kinetics of phase transformations of undercooled austenite by continuous cooling and the kinetics of phase transformations during heating from the quenched state (tempering) of this steel was analyzed from dilatometric tests. It has been demonstrated that the new steel, after applying of a proper heat treatment, poseses properties (especially the hardness) which meet expectations of industrial community with regard to tools used in hot and cold working. It is anticipated to use this steel for manufacturing of case-hardened tools.
Keywords: tool steel, dilatometer, phase transformations, CCT diagram, heat treatment, mechanical properties

W artykule przedstawiono wyniki badań własności mechanicznych nowej, nadeutektoidalnej stali Mn-Cr-Mo-V. Badania te obejmowały: próbę rozciągania, udarności oraz pomiary twardości. Dodatkowo, na podstawie badań dylatometrycznych, opisano kinetykę przemian fazowych przechłodzonego austenitu przy chłodzeniu ciągłym oraz kinetykę przemian fazowych podczas nagrzewania ze stanu zahartowanego (odpuszczania) tej stali. Wykazano, że nowa stal, po zastosowaniu odpowiedniej obróbki cieplnej, umożliwia osiągnięcie własności (a zwłaszcza twardości) oczekiwanych przez użytkowników narzędzi stosowanych w przeróbce plastycznej na zimno i na gorąco. Przewiduje się zastosowanie tej stali na narzędzia hartowane jedynie w warstwie zewnętrznej.

1. Introduction

The hypereutectoid steels belong to elementary materials used for production of tools for metal forming. The basic requirements for these steels are: sufficient hardenability [1], wear resistance [2, 3] as high as possible strength [4, 5] and fracture toughness [6, 7]. However the most important requirement for these steels is high hardness. The hardness depends primarily on carbon content in the steel [1, 4, 5, 8]. According to Ref. [8] the highest hardness possible to reach for unalloyed steel is about 800 HV (64 HRC) at concentration of about 0.7% of carbon. Higher hardness may be obtained as a result of secondary hardening (e.g. in high-speed steels or in hot worked tool steels) or as a result of the presence in steel microstructure some amount of hard, undissolved carbides [4÷7, 9].

Some users of mechanical working tools (e.g. rolls) require the hardness as high as 66÷67.5 HRC which corresponds to the hardness of 865÷920 HV or 93÷96 HSC. The high hardness is essential in applications for working rolls designed for cold rolling of car body sheets and for working rolls in zinc and aluminum rolling mills.

Such hardness may be obtained after quench hardening of hypereutectoid steels (usually from temperatures about 50°C higher than A_{c1k}) followed by low-temperature tempering (stress-relief tempering) at 100÷150°C.

Within the framework of this study it was attempted to evaluate selected mechanical properties of a new, hypereutectoid Mn-Cr-Mo-V steel, for verification of its potential usage in manufacturing industry, which required processing tools having the highest hardness.

2. Research material

Results obtained from former studies [1, 9÷12] conducted in the Department of Physical and Powder Metallurgy at AGH University of Science and Technology regarding quantitative influence of alloying el-

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ements on the microstructure and properties of different class of steel as well as application of computer software package "PROSTAL", permit to design the chemical composition of a new grade of alloy steel, allowing to reach the hardness value close to 880 HV upon quench-hardening. A trial casting of the steel with the calculated composition has been prepared. Its chemical composition is presented in Table 1. It is a manganese-chromium-molybdenum-vanadium high-carbon steel.

The steel has been designed primarily for production of high hardness tools for cold working, however, it is anticipated to use it also for (after suitably slow cooling and successive annealing) production of tools with high fraction of carbides, designed for hot processing (with hardness of about 300 HV).

TABLE 1

Chemical composition of the investigated steel, % by mass

C	Mn	Si	P	S	Cr	Mo	V	Al	N
1.25	2.05	0.25	0.02	0.015	1.61	0.39	0.44	0.025	0.005

The trial ingot, of about 50 kg, has been made in open induction furnace. The ingot has been forged into rods with a cross section of 20×35 mm. The rods have been subsequently spheroidized.

3. Experimental procedure

The determination of critical temperatures of the new steel in the annealed state was performed with dilatometric method using LS4 optical dilatometer. The samples with dimensions of Ø4×25 mm were heated to 1100°C at the rate of 3°C/min. The changes in samples elongation induced by the temperature change were recorded on the photographic plate.

On the basis of the recorded dilatograms the austenitizing temperature of the steel was determined as 800°C, i.e. A_{C1k} + 55°C. This temperature was further verified metallographically by observations of microstructure of samples (hardening series) quenched from progresively increased temperature.

The research of kinetics of the phase transformations of the undercooled austenite has been performed with a dilatometric method. The Continuous-Cooling-Transformation (CCT) diagram (for steel austenitized at 800°C) was made by means of a LS4 optical dilatometer. The samples (Ø4×25 mm) were heated with the rate of 3°C/s to the temperature given above, held for 1200 s and next cooled down with different rates, governed by a regulated blow of argon.

The kinetics of phase transformations upon tempering was studied by means of dilatometric method using a DT1000 dilatometer manufactured by a French company Adamel. The changes in samples' elongation induced by temperature were recorded by a computer. On the basis of the first differentiative calculated from the obtained curves it was possible to precisely define the temperatures of the beginning and the end of particular transformations.

In order to produce Continuous-Heating-Transformation (CHT) diagram, samples of the examined alloys with the size of Ø2×12 mm were quenched in water from 800°C. The quenched samples were then heated in the dilatometer to 700°C with the following rates: 0.05, 0.1, 0.5, 1; 5, 10, 15, 35°C/s.

Table 2 presents selected cooling methods of the new steel from 800°C and the temperature of its subsequent stress-relief tempering to obtain expected hardness, i.e. about 880 and 300 HV.

In order to obtain the hardness of about 880 HV it is proposed to apply quench-hardening in water with subsequent stress-relief tempering at 100°C.

However, to obtain the hardness of about 300 HV it is proposed to apply cooling down at the rate of 550°C/h, and next carry out the stress-relief tempering at 550°C.

TABLE 2

Selected cooling and stress-relief tempering methods of the new steel to obtain expected hardness

Austenitizing (temperature and time)	Cooling methods	Stress-relief tempering temperature (t=2h)	Expected hardness
800°C/30 min.	water	100	~880 HV30
800°C/30 min.	500°C/h	550	~300 HV30

Mechanical tests of the new steel comprised tensile test, impact toughness test and hardness measurements. Static tensile test has been performed using a computer controlled Instron testing machine. During this test the following data have been determined: tensile strength (R_m), yield point (R_e), elongation (A) and reduction of area (Z). Proportional test pieces have been used with initial diameter of 4 mm.

Impact toughness tests have been performed with Charpy method on specimens (10×10×55 mm) with 2 mm deep and U-notch with 1 mm root angle. They have been tested with pendulum with energy of 15 J.

Hardness has been measured using Vickers apparatus (HPO 250 type) with 30 kG (294 N) indender load.

The microstructures of the steel in spheroidizing condition and after cooling at different rates from 800°C (representing subsequent cooling curves from CCT diagram) have been digitally recorded using Zeiss Axiovert 200 MAT optical microscope.

The processes of annealing, austenitizing and stress-relief tempering have been performed in RHF 16/19 type Carbolite laboratory furnace.

4. Results and discussion

The critical temperatures Ac_{1p}, Ac_{1k} and Ac_{cm} of the new steel in a softened state have been determined on the basis of its microstructure (Figure 1) and hardness measurements. The spheroidizing was performed not to only to reduce the hardness (in as-received condition 332 HV) but also to remove from its microstructure network of hypereutectoid cementite.

TABLE 3

Results of hardness measurements and critical temperatures after spheroidizing

State of steel	HV 30	Critical temperatures, °C		
		Ac_{1p}	Ac_{1k}	Ac_{cm}
Spheroidizing	211	720	745	1050

Results of hardness measurements and critical temperatures after spheroidizing are presented in Table 3.

The application of spheroidizing resulted in almost complete elimination of hypereutectoid cementite network and in obtaining the structure of the spheroidite as well as reducing the steel hardness from 332 to 211 HV. The microstructure after spheroidizing has been an initial one for further heat treatment of the specimens designed for the evaluation of the kinetics of phase transformations of austenite by continuous cooling, the kinetics of phase transformations taking place during tempering of this steel and for the mechanical testing.

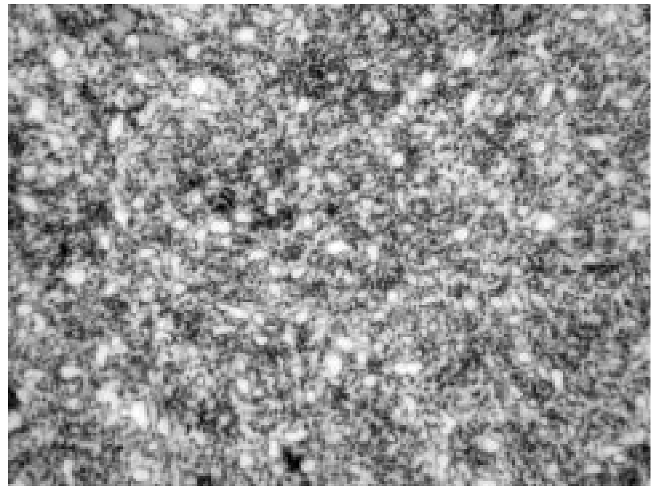


Fig. 1. Microstructure of new steel after spheroidizing; 630x

Figure 2 shows the CCT diagram of the trial steel sketched for austenitizing temperature of 800°C. It was assumed that the austenite stability within the range between the pearlite and bainite transformation is infinite. For the highest cooling rates, i.e. 6°C/s (cooling in air) and 3°C/s, the critical cooling rate has been overcome and austenite transformed into martensite only. The hardness for such specimens were: 796 and 771 HV respectively. From the cooling rate of 0.6°C/s on, the transformation of undercooled austenite begin with the formation of bainite rather than martensite. For the lowest cooling rate (0.04°C/s) the precipitation of pearlite was observed while the hardness of specimen cooled in such a way was 278 HV. The Ms temperature in the trial steel has been estimated for 210°C.

Figure 3 shows metallographic documentation of specimen microstructures obtained by cooling down from 800°C at different rates.

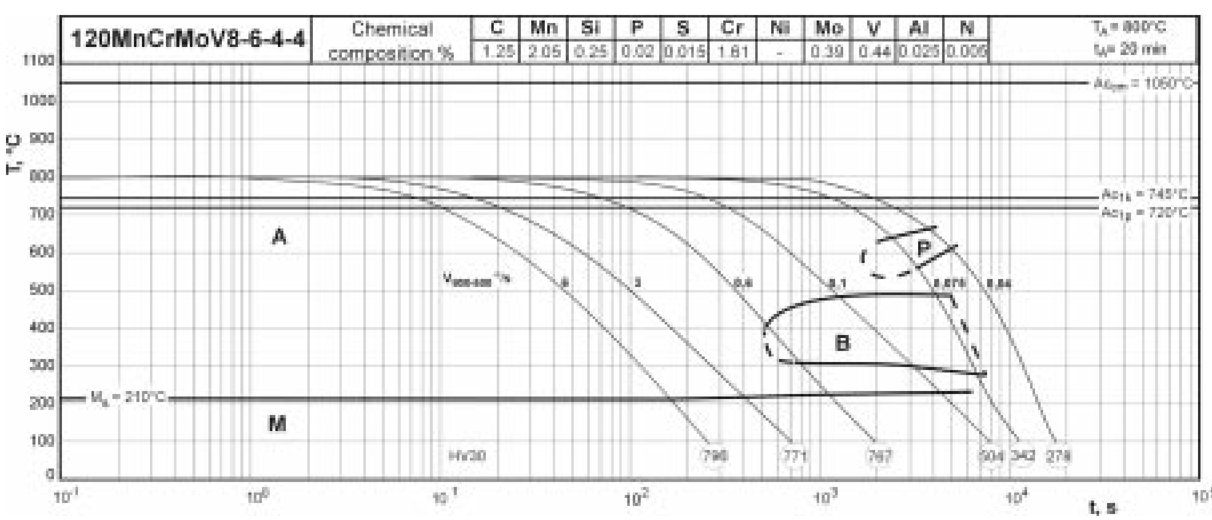


Fig. 2. CCT diagram of the investigated steel austenitized at 800°C, made by means of the dilatometric method

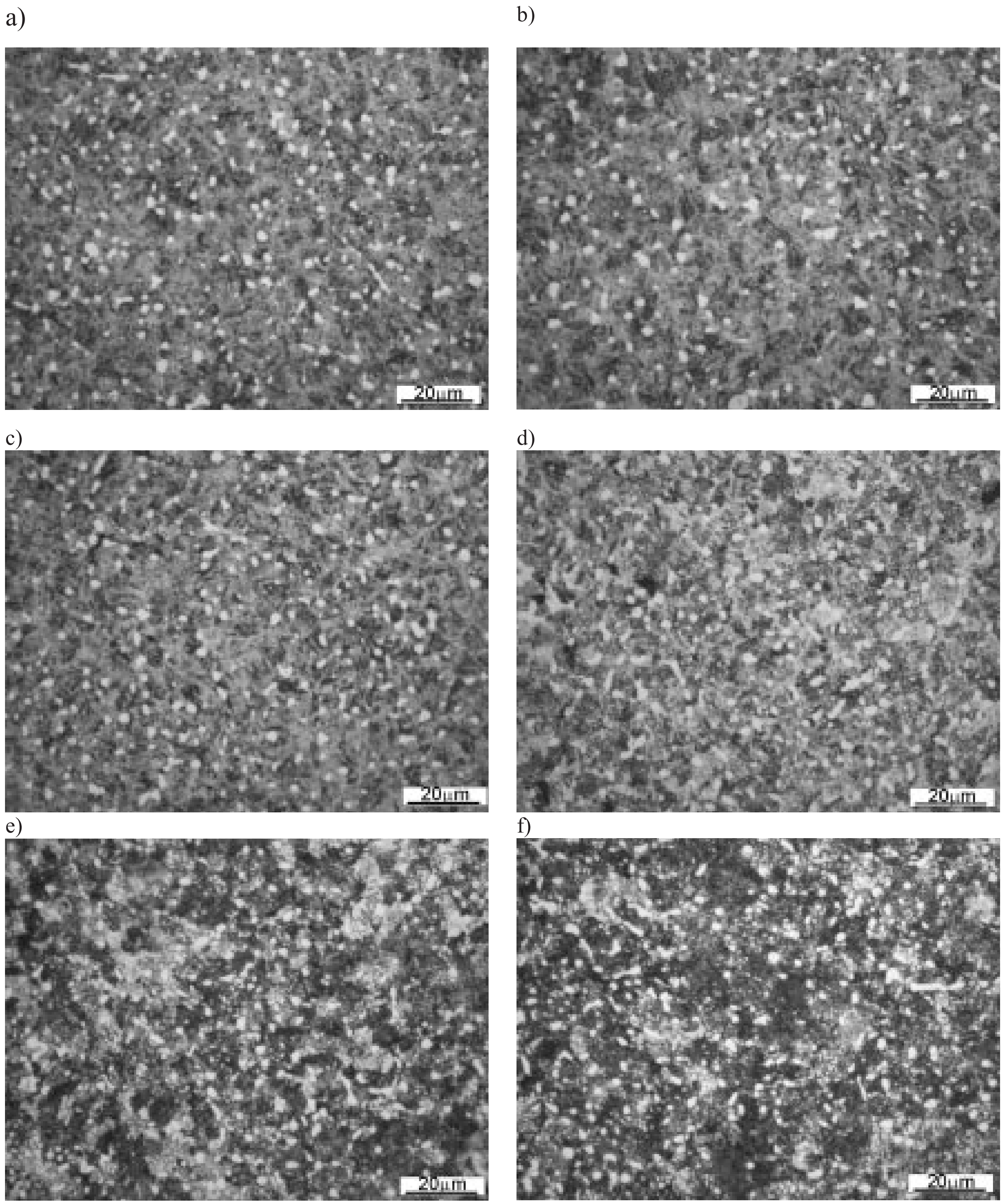


Fig. 3. Microstructure of the investigated steel cooled with cooling rate: a – 6°C/s, b – 3°C/s, c – 0.6°C/s, d – 0.1°C/s, e – 0.075°C/s, f – 0.040°C/s

It is seen that, the steel microstructure changes from martensite – for the highest cooling rate, i.e. 6°C/s (Fig. 3a), up to pearlite structure – for cooling rate of 0.04°C/s (Fig. 3f). Within the whole range of cooling rates there are numerous carbide particles observed in specimens' microstructure. Figure 4 presents, the full CHT diagram of the trial steel made for its heating from the quenched state preceding by austenitizing temperature 800°C.

In the Mn-Cr-Mo-V steel containing 1.25% C, the following phases are present: probably ε carbides, M_3C cementite and retained austenite (RA) (marked area). In the whole range of applied heating rates, the samples' shrinkage related to the ε carbide precipitation was detected. It started at about 100°C (ε_s) and as early as

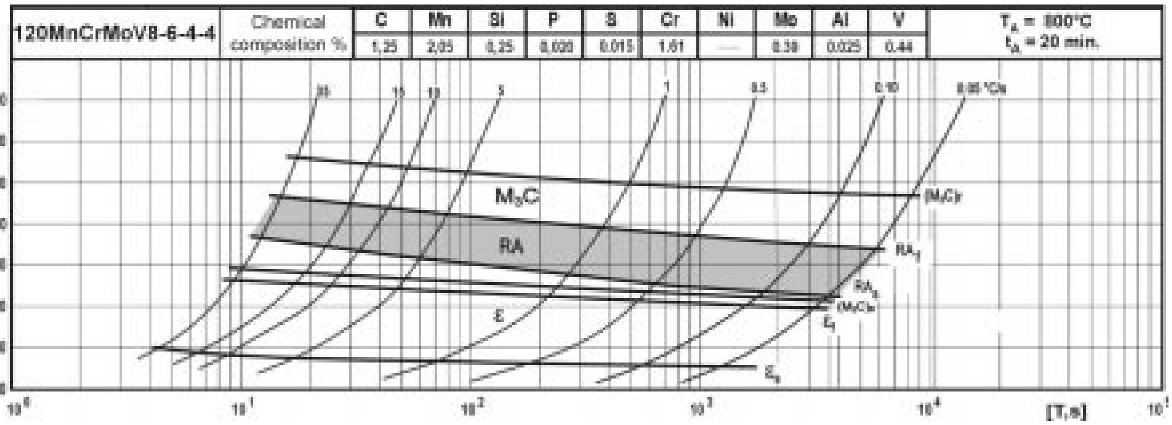


Fig. 4. CHT diagram of the investigated steel formerly quench hardened from temperature 800°C

at 60°C for heating rates of 0.05°C/s and 35°C/s, respectively. The retained austenite transformation took place in the cementite precipitation range. The beginning temperature of cementite precipitation $(M_3C)_s$ was about 30°C higher than the end-temperature of ε carbide precipitation (ε_f). All transformations taking place during tempering move to higher temperatures, when the heating rates increased.

As it has been mentioned before, the specimens for mechanical testing have been austenitized at temperature Ac_{1k} + 55°C=800°C. For the specimens which were expected to have the hardness of about 880 HV the water has been used as quenching medium while stress-relief tempering has been conducted at 100°C. The hardness of the new steel after such heat treatment was 886 HV.

In order to achieve the anticipated hardness of about 300 HV specimens of the new steel ought to be cooled from 800°C at the rate of 500°C/h and than subjected to stress-relief tempering at 550°C. Then the hardness is 316 HV.

Table 4 presents detailed results of mechanical properties of the new steel after application of both versions of heat treatment.

TABLE 4

Mechanical properties of the new steel

Heat treatment	HV30	R_m MPa	R_e MPa	A %	Z %	KCU2 J/cm^2
800°C/30min./quenched in water + 100°C/2h/cooled in air	886	1165	–	–	–	5.5
800°C/30min./cooled 500°C/h + 550°C/2h/cooled in air	316	1055	663	8.1	15.8	18.9

The new steel after quenching in water from 800°C and stress-relief tempering at 100°C with hardness of 886 HV demonstrated tensile strength (R_m) equal to 1165 MPa. The impact toughness in this state of heat treatment has been evaluated to merely 5.5 J/cm^2 (referring it to section in notch equaling to 0.8 cm^2).

The stress-strain curve in tension of the new steel after application of previously described heat treatment resulted in the hardness of 886 HV has been presented in Figure 6a. The diagram is linear within the whole range of strain.

After heat treatment of the new steel (cooling from 800°C at the rate of 500°C/h and stress-relief tempering at 550°C) the impact toughness is 18.9 J/cm^2 while tensile strength is 1055 MPa. In this case the break of the impact toughness specimens is initiated at the bottom of the notch (Fig. 5), while during tensile test the well-defined yield point is revealed (Fig. 6b). The yield strength is 663 MPa, while the elongation reaches 8.1%.

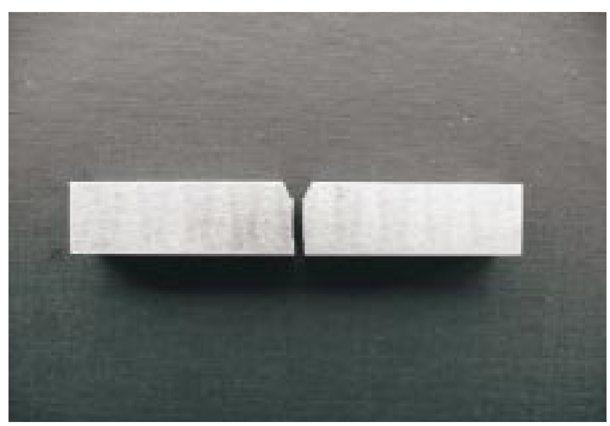
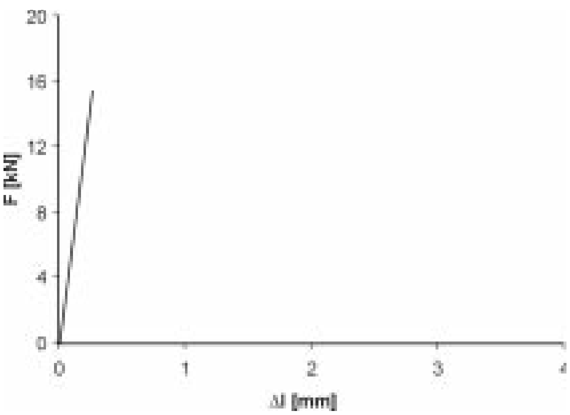


Fig. 5. Investigated steel after impact toughness tests: austenitized 800°C/30min./cooled 500°C/h and stress-relief tempered 550°C/2h

Results of mechanical testing of the new steel presented in Table 4 will decide in the future about its potential application for the production of mechanical working tools. However, also the results of wear resistance testing of this steel grade will have significant meaning. Nevertheless, one may depend on strong influence of the undissolved carbides on this property. Testing of wear mechanisms of the new steel will be a subject of the separate study.

a)



b)

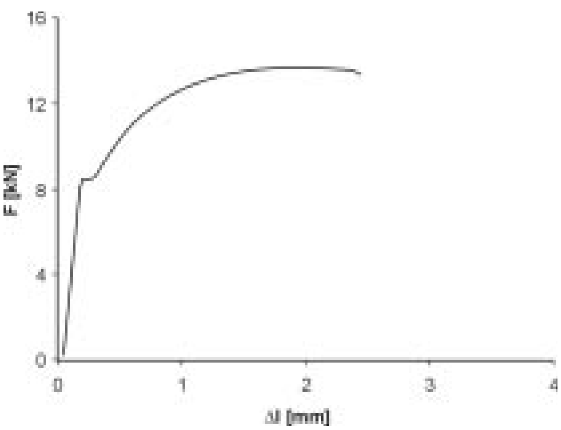


Fig. 6. The results of tensile test after heat treatment of new steel: a) austenitized 800°C/30min./quenched in water and stress-relief tempered 100°C/2h b) austenitized 800°C/30min./cooled 500°C/h and stress-relief tempered 550°C/2h

5. Conclusions

The presented in this study results of mechanical properties of hypereutectoid steel containing 1.25% C; 2.05% Mn; 1.61% Cr; 0.39% Mo; 0.44% V allow us to state that:

1. It is possible to obtain the hardness of steel which suite the needs of cold and hot working manufacturers.
2. Application of water quenching with subsequent stress-relief tempering at 100°C results in hardness of 886 HV (i.e. ca. 66.7 HRC). This value makes the steel applicable for production of tools (rolls) for cold working of metals.
3. Application of cooling at the rate of 500°C/h combined with stress-relief tempering at 550°C results in hardness of 316 HV. After such heat treatment, the new steel may be used for production of the tools (rolls) for hot working.
4. The new steel may be used for production of both surface hardened tools (with remaining of its ductile core) and the tools heat treated by volume to desired hardness.

REFERENCES

[1] J. P a c y n a, Projektowanie składów chemicznych stali, AGH Kraków, 1997.

[2] K.H. Z u m G a h r, Microstructure and wear of materials, Tribology, Amsterdam-Oxford-Tokio **10**, 227 (1987).

[3] H. B e r n s, Wear resistant steels, Steel, A Handbook for Materials Researched and Engineering, Springer-Verlag-Stahleisen mbH **2**, 374 (1993).

[4] S. W i l m e s, H.J. B e c k e r, R. K r u m p h o l z, W. V e r d e r b e r, Tool Steels, Steel, A Handbook for Materials Researched and Engineering, Springer-Verlag-Stahleisen mbH **2**, 302 (1993).

[5] A.K. S i n h a, Physical Metallurgy Handbook, The Mc Graw-Hill Companies, Inc., 2003.

[6] J. P a c y n a, L. W i t e k, Steel Research **59**, 2, 68 (1988).

[7] J. P a c y n a, Metaloznawstwo pękania stali narzędziowych, Metalurgia i Odlewnictwo 120 (1988).

[8] A.P. G u l a j e v, Mietałłoviedienie, Mietałłurgija, Moskva, (1986).

[9] R. D ą b r o w s k i, The effect of vanadium on the structure and properties of quenched and tempered model alloy steels, Ph.D. Thesis, AGH University of Science and Technology, Kraków, 2002.

[10] A. J ę d r z e j e w s k a - S t r a c h, Manganium influence upon the kinetics of phase transformations, structure and qualities of model construction steel alloys, Ph.D. Thesis, AGH University of Science and Technology, Kraków, 1995.

[11] M. S t r a c h, The structure and qualities of silicon steels evaluated on the basis research of model alloys of various silicon and carbon concentration, Ph.D. Thesis, AGH University of Science and Technology, Kraków, 1995.

[12] M. D u b i e l, Phase transformation in model alloys with chromium imitating the matrix of quenched construction and rustless steels, Ph.D. Thesis, AGH University of Science and Technology, Kraków, 1996.

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