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TEMPERING TEMPERATURE EFFECTS ON HARDNESS AND IMPACT TOUGHNESS OF 56NiCrMo7 STEEL

WPŁYW TEMPERATURY ODPUSZCZANIA NA TWARDOŚĆ I UDARNOŚĆ STALI 56NiCrMo7

The assessment of the effect of tempering temperature on hardness and impact toughness of a 56NiCrMo7 grade hot work tool steel was presented in the paper. It has been found that the investigated steel, after quenching in oil from 800°C, softens quite slowly upon tempering within the range between 100 and 675°C, which was confirmed not only by hardness measurements but also by observed changes occurring in its microstructure, whereas the impact energy (KV) absorbed by the test specimen increases with temperature, achieving >66J after tempering at 675°C. The changes observed in the character of the fracture surfaces allows of interpretation of the impact test results for the whole range of tempering temperatures.

Keywords: hot work tool steel, heat treatment, microstructure, hardness, impact toughness, fractographic examination

W artykule przedstawiono wyniki badań na temat wpływu temperatury odpuszczania na twardość i udarność stali narzędziowej do pracy na gorąco w gatunku 56NiCrMo7. Badania wykonano dla wybranej temperatury austenityzowania równej 800 °C. Wykazano, że badana stal zahartowana w oleju od tej temperatury a następnie odpuszczona w zakresie 100÷675 °C mięknie dość wolno, co potwierdziły nie tylko wyniki pomiarów twardości ale również obserwacje zmian zachodzących w jej mikrostrukturze. Praca złamania (KV) próbki udarnościowej rośnie ze wzrostem temperatury odpuszczania, przekraczając 66 J po odpuszczaniu w 675°C. Potwierdzeniem uzyskanych wyników badań udarności są zmiany zaobserwowane w charakterze przełomów próbek w całym zakresie temperatur odpuszczania.

1. Introduction

Despite of a fast development of material engineering and searching for new metallic materials for various tools, such as: moulding tools, dies, punches, shear knives, etc., the hot work tool steels are still widely used [1÷6]. A properly designed chemical composition and heat treatment conditions ensure that these steels attain the required combination of properties, such as: high hardness and fracture toughness, high strength at elevated temperatures, structural stability, and resistance to formation of heat cracks [2÷9]. Extensive qualitative and quantitative research into the effects of various alloying elements on the microstructure and properties of ferrous alloys have been carried out at the Department of Physical Metallurgy and Powder Metallurgy, AGH, over the past years [7,10,11]. Most of the work was focused on model alloys, both structural steels and tool steels for cold and hot working conditions, having a specially designed chemical composition in which only a concentration of one element was varied [7,10,11].

The 56NiCrMo7 steel is a grade designed for service at elevated temperatures, commonly used for forming dies and anvils for hammers in drop forging shops in the majority of industrialized countries. The steel has to be heat treated to gain the optimum combination of high hardness and good ductility so that the tool can withstand the large pressure and vibrations during a relatively short contact with the forged metal. Under industrial conditions it is oil quenched from 800-860°C and tempered between 520 and 600°C. As documented in ref [12], the maximum hardness of 802 HV30 was found after quenching from austenitizing temperature 860°C although there is no information on the influence of the tempering temperature on the properties of the 56NiCrMo7 steel. Therefore the main objective of this work is to extend the existing knowledge of the interdependence between the heat treatment conditions and properties of the 56NiCrMo7 steel.

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TABLE 1

Chemical composition of 56NiCrMo7 steel

	Chemical composition (wt.%)								
	C	Mn	Si	P	S	Cr	Ni	Cu	Mo
PN-EN ISO 4957:2002U specification	0.50÷0.6	0.50÷0.80	0.15÷0.35	Max. 0.03	Max. 0.03	0.50÷0.80	1.40÷1.80	Max. 0.30	0.15÷0.30
Analysis	0.56	0.72	0.17	0.010	0.005	0.69	1.68	0.20	0.20

2. Experimental procedure

The steel used in this work was supplied by the Tool Plant ”KUŹNIA” S.A. in Sułkowice in the form of 13 x 40 x 200 mm bars in the soft annealing condition (heat to 675°C at 30°C/min, dwell at temperature for 3 hours, cool down with furnace to room temperature). As shown in Table 1 its chemical composition was found to meet the PN-EN ISO 4957:2002U standard requirements.

The experimental specimens bars of size 11,5x11,5x55 mm were austenitized in a laboratory *Carbolite RHF1600* furnace for 1 hour at 800°C and oil quenched. Then specimens were tempered for 2 hours at 100, 200, 300, 400, 500, 600, 650 and 675°C (3 specimens at each temperature). After heat treatment the samples were profile grinded on the final dimensions of 10x10x55 mm with following cutting of Charpy V notch. The impact tests were performed according to PN-EN 10045-1:1994, using the 15 kGm Charpy tester.

The Charpy test bars along were then subjected to the Vickers hardness test.

The Vickers hardness tests were carried out on the *HPO250* tester by producing three indentations under a load of 30kG (294N) on each fine grounded specimen. The nine VHN values were then used to calculate the arithmetic mean for given tempering temperature.

The microstructure of 56NiCrMo7 in both as-quenched and quenched and tempered state was observed using the light microscope *Zeis Axiovert 200 MAT*. The metallographic specimens were prepared in four steps, i.e. pre-grinding on a magnetic grinder, grinding on abrasive papers, polishing with diamond pastes and fine-polishing by means of Al_2O_3 suspension. After etching in 4% nital, their microstructure was observed at 950x magnification.

In order better to examine the tempering temperature effects on the impact test results the fracture surfaces of the Charpy bars were also observed at 5000x magnification using the *Hitachi 3500N* scanning electron microscope.

3. Results and discussion

According to ref [12], the austenitizing temperature of 800°C is the lowest in the range usually applied for 56NiCrMo7 under industrial conditions (800÷860°C) and lies 40°C above the temperature of the end of the ferrite-to-austenite transformation (Ac_3).

The experimental steel was delivered in soft annealed condition (209 HV30). Its microstructure consisted of pearlite and a small fraction of ferrite.

The microstructure of the steel in as-quenched condition is shown in Fig. 1.

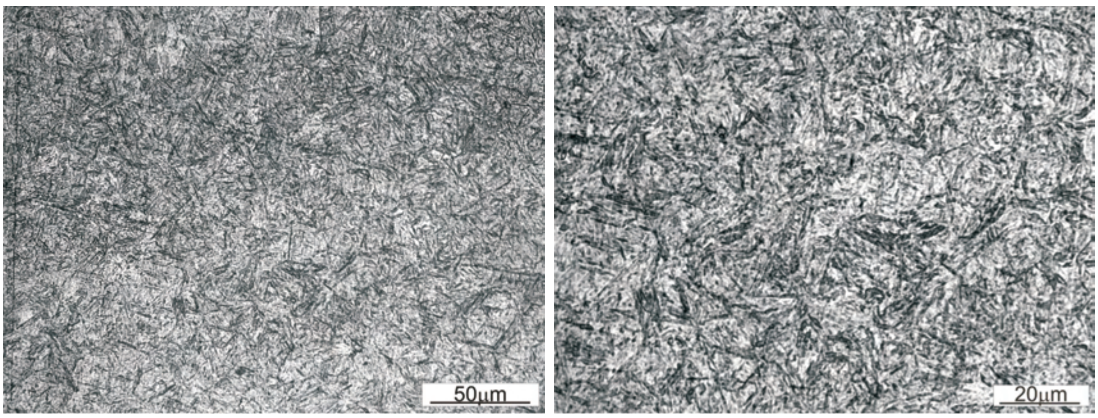


Fig. 1. Photographs of the microstructure of the 56NiCrMo7 steel sample quenched in oil from 800°C

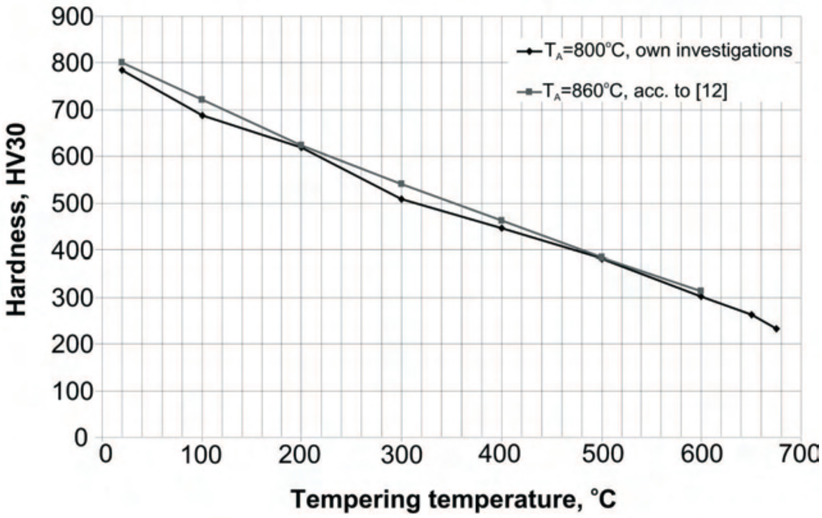


Fig. 2. Influence of the tempering temperature on hardness (HV30) of the 56NiCrMo7 steel samples quenched in oil from 800°C (own investigations) and from 860°C (acc. to [12])

As seen in Fig. 1, after quenching from 800°C the martensite grows in a fine acicular shape, which indicates fine-grained structure of the prior austenite. The carbon content (0.56%) and adequate combination of chromium, nickel and molybdenum ensure sufficiently high hardenability of 56NiCrMo7 steel to use oil as the cooling medium.

As shown in Fig. 2 the macroscopic hardness of oil-quenched specimens is 784 HV30, whereas the dependence of hardness on tempering temperature has a nearly rectilinear character decreasing from 690 to 232 HV for specimens tempered at 100 and 675°C, respectively. The grey curve in Fig. 2 represents results adapted from ref [12], which were obtained for the same steel grade austenitized at 860°C.

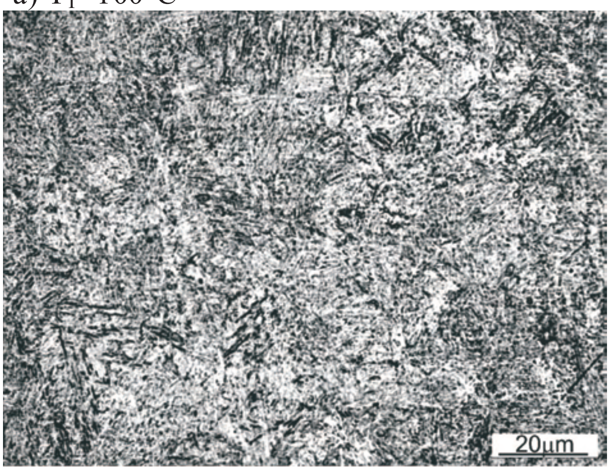
As it is evident from Fig. 2, the tested steel softens fairly slowly and still retains hardness of around 300 HV after tempering at 600°C. This can be related to the presence of molybdenum in the steel although its amount (0.2% Mo) is insufficient to obtain a secondary hardening effect after tempering between 500 and 650°C, which usually occurs in hot work tool steels.

It should be noted, that the as-tempered hardness of specimens quenched from 800°C is slightly lower compared to their counterparts austenitized at 860°C [12].

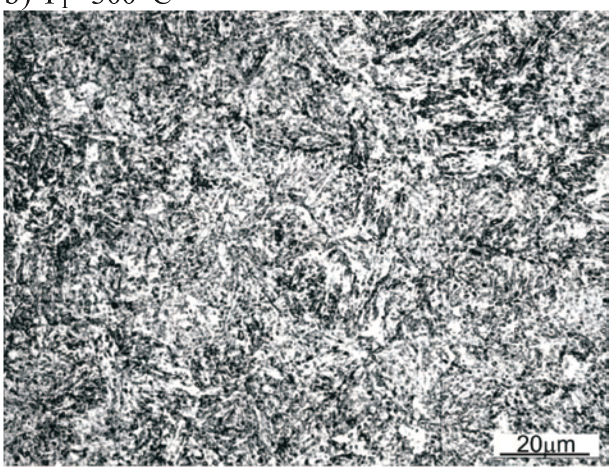
Microstructures of the selected specimens are shown in Fig. 3.

Tempering at a temperature as low as 100°C reliefs stresses in martensite therefore the fine, acicular, low tempered martensite (Fig. 3a) exhibits similarity to martensite obtained directly after quenching from 800°C (see Fig. 1). Increasing the tempering temperature to 300°C brings about a marked decrease in hardness from 690 to 508 HV. The microstructure is still acicular and exhibits similarity to lower bainite (Fig. 3 b). After tempering at 400°C martensite loses the acicular character (Fig. 3 c), whereas between 500 and 600°C sorbit forms (Figs 3 d÷f).

a) T_T=100°C



b) T_T=300°C



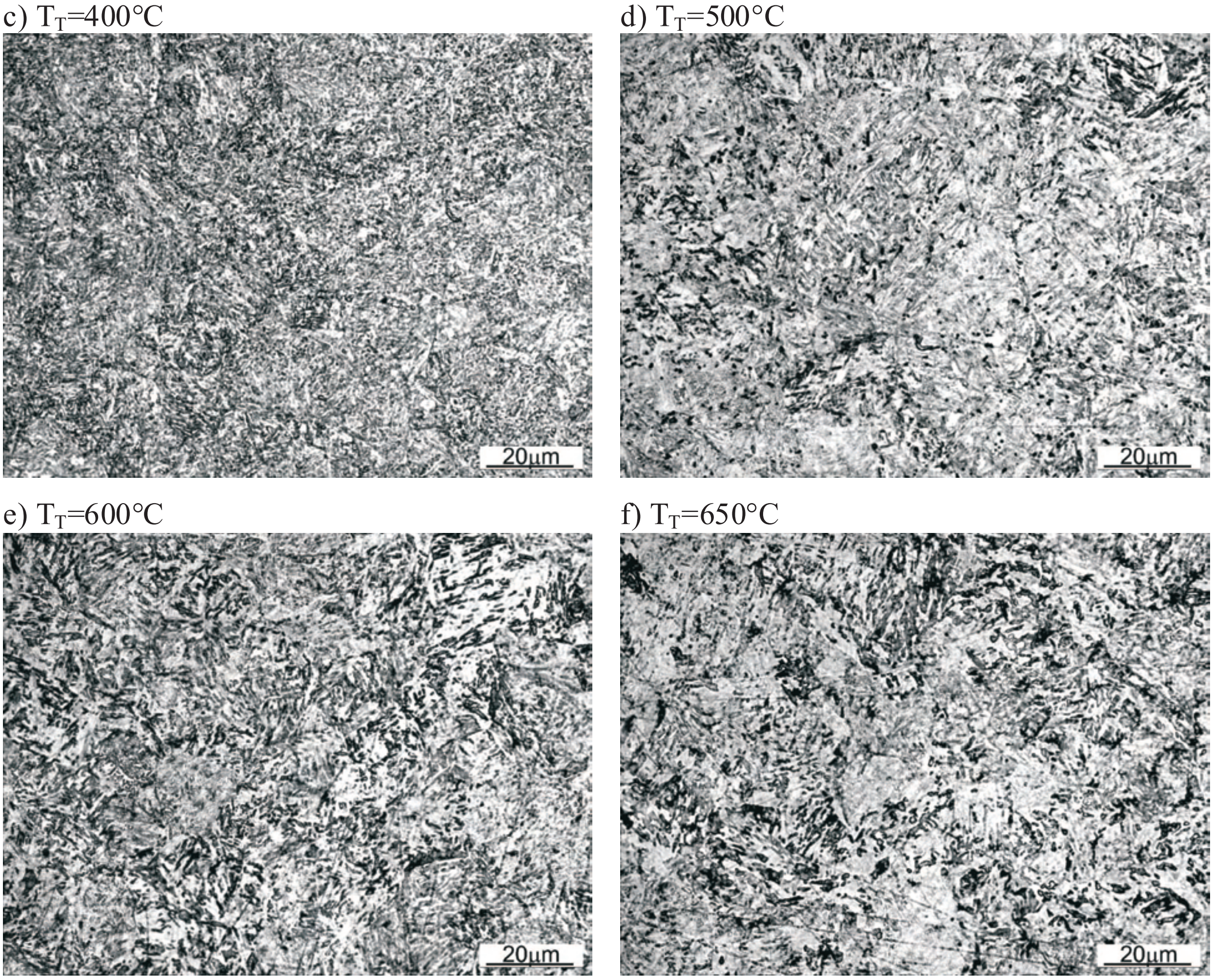


Fig. 3. Photographs of microstructures of the selected 56NiCrMo7 steel samples tempered in the temperature range 100÷650°C, previously quenched in oil from 800°C

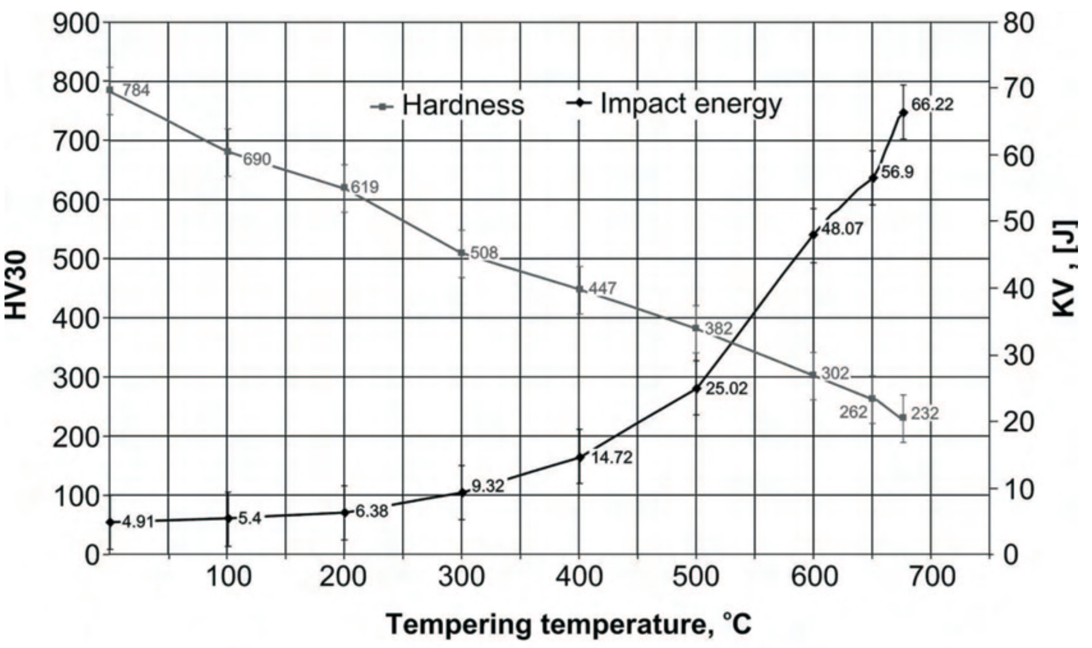
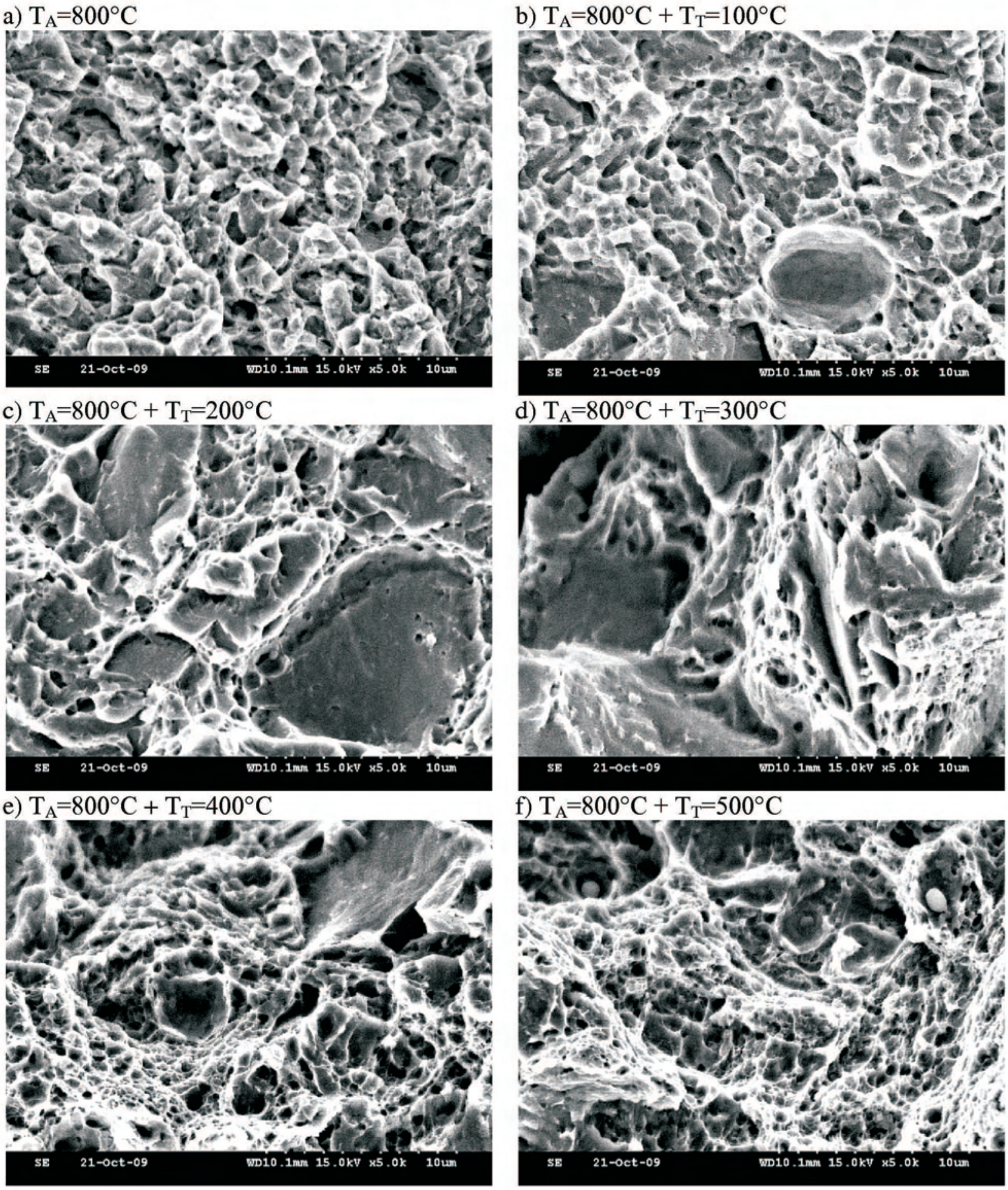


Fig. 4. Influence of the tempering temperature on impact energy (KV) and hardness (HV30) of the 56NiCrMo7 steel samples, quenched in oil from a temperature of 800°C


a) T_A=800°C
SE 21-Oct-09 WD10.1mm 15.0kV x5.0k 10um
b) T_A=800°C + T_T=100°C
SE 21-Oct-09 WD10.1mm 15.0kV x5.0k 10um
c) T_A=800°C + T_T=200°C
SE 21-Oct-09 WD10.1mm 15.0kV x5.0k 10um
d) T_A=800°C + T_T=300°C
SE 21-Oct-09 WD10.1mm 15.0kV x5.0k 10um
e) T_A=800°C + T_T=400°C
SE 21-Oct-09 WD10.1mm 15.0kV x5.0k 10um
f) T_A=800°C + T_T=500°C
SE 21-Oct-09 WD10.1mm 15.0kV x5.0k 10um

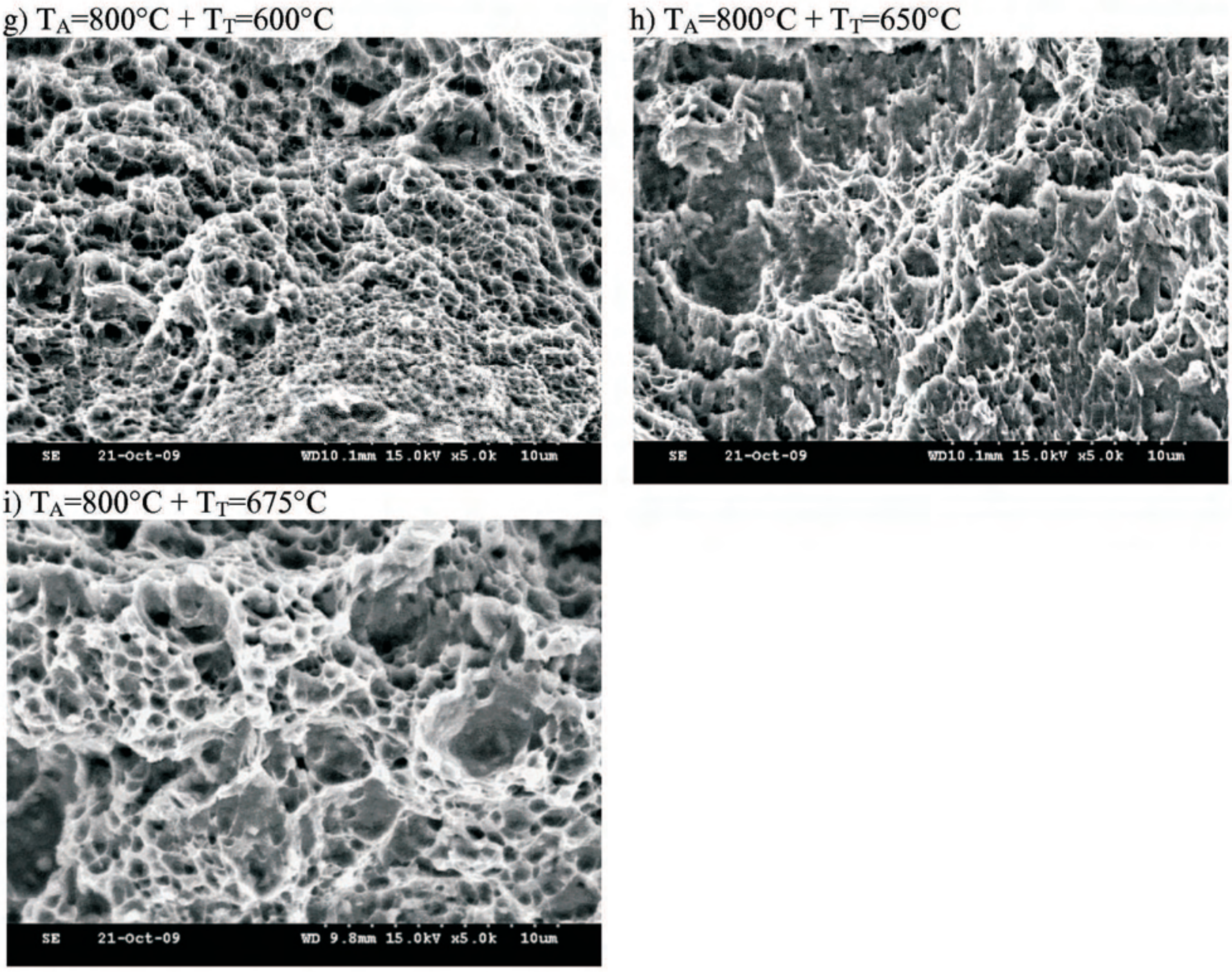


Fig. 5. Photographs of the 56NiCrMo7 steel sample fractures: quenched in oil from 800°C (Fig. 5 a) and then tempered for 2 hours at temperatures: 100, 200, 300, 400, 500, 600, 650 and 675°C (Fig. 5 b÷i)

The effect of tempering temperature on impact toughness (KV) and hardness (HV30) is demonstrated in Fig. 4.

As a rule, the impact toughness of the 56NiCrMo7 steel increases with the tempering temperature. The impact energy absorbed by a V-notched bar in as-quenched condition is 4.9 J and only slightly increases after tempering at 100°C. A marked increase in the absorbed energy is observed at 300°C (9.32 J), whereas KV steeply rises above 500°C (25 J) to reach 66 J after tempering at 675°C. This is due to recrystallisation and, presumably, precipitation and coagulation of alloy cementite which processes occur at this temperature range.

It should be noted that due to the presence of 0.2% Mo the 56NiCrMo7 grade is immune to temper brittleness [2÷5].

The measurements of impact toughness were followed by fractographic studies in order to indentify the fracture mechanism by which failure had occurred. Fig. 5 presents fracture surfaces of Charpy bars which were either used in as-quenched condition (Fig. 5a) or quenched and tempered (Fig. 5b÷i). In both the as-quenched state (Fig. 5 a) and tempered at 100^{o}C (Fig. 5 b) a brittle fracture is observed. After tempering at 200, 300 and 400°C (Fig. 5c÷e) the fracture surface has a mixed character. A local occurrence of a ductile fracture is probably caused by nickel dissolved in the matrix, while flat areas (related to a brittle fracture) presumably correspond to the formation of fresh martensite through thermal destabilization of retained austenite. Nevertheless, the presence of such flat areas did not decrease the impact toughness within the tempering temperature range 200÷400^{o}C (see Fig. 4.). By increasing the tempering temperature from 500^{o}C (Fig. 5 f) up to 675^{o}C (Fig. 5 i) it was possible to increase the proportion of the ductile dimpled surface. Large dimples seen in Fig. 5f formed due to separation of the metal at interfaces between the matrix and large inclusions (presumably MnS). In general, the fracture surfaces seen in bars tempered between 500 and 675^{o}C have a ductile character. This coincides with high fracture toughness of the 56NiCrMo7 steel tempered within this temperature range.

4. Conclusions

1. The 56NiCrMo7 steel quenched in oil from 800°C and tempered between 100 and 675°C is characterized by the Vickers hardness between 690 HV (T_T=100°C) and 232 HV (T_T=675°C).
2. By increasing the tempering temperature from 100 to 675°C it is possible to markedly increase the steel toughness.
3. The fracture surface characteristic features change with increasing the tempering temperatures. Below 200°C the steel fails in a brittle mode, between 200 and 400°C fracture has a mixed character with increasing proportion of plastically deformed material, whereas at 500°C and beyond dimpled ductile fracture prevail.
4. A steep increase of impact energy takes place after tempering above 500°C which can be associated with the absence of brittle martensite in the steel.

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