

Retained austenite in the cracking process of 70MnCrMoV9-2-4-2 tempered steel

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Properties

ABSTRACT

Purpose: The aim of this study was a review of opinions molded within last 35 years on a part of steel cracking process played by retained austenite.

Design/methodology/approach: Dependencies between volume fraction of retained austenite, its stability, hardness, fracture toughness, and tempering temperature of hardened 70MnCrMoV9-2-4-2 steel were determined. On the ground of analysis of those dependencies the influence of retained austenite on fracture toughness of tested steel was investigated.

Findings: It was found that retained austenite remaining in the structure of tested steel after quenching increased its fracture toughness on directly proportional way to its volume fraction. Advantageous influence of this phase was also found after tempering tested steel at temperatures within the range of 120-400°C.

Research limitations/implications: The results of investigation presented in this paper may enrich and complement the knowledge about the part played by this phase in steel cracking process. It was pointed out that most beneficial influence of retained austenite exists when tested steel after hardening is low-tempered. At that moment the highest stabilization of the phase occurs. While at tempering temperatures above 220°C it was indicated that it is possible to combine retained austenite transition and irreversible tempering brittleness.

Practical implications: Research results presented in this paper let hope that know-how of such heat treatment, which would make possible to stabilize this phase in the structure of hardened steels, would contribute not only to restrain temper brittleness in these steels but even to complete elimination of this adverse phenomenon.

Originality/value: On the basis of own research, the authors have verified the opinions, presenting original point of view on the issue of presence of retained austenite in the structure, its stability and the influence on fracture toughness of tool steel.

Keywords: Tool materials; Fracture toughness; Retained austenite; Stability of retained austenite; Temper brittleness

1. Introduction

Despite 35 years of research in various scientific institutions all over the world, so far, there is no common and unequivocal opinion on part played by retained austenite in the process of steel cracking. Such condition of the issue seems to be surprising, because fracture toughness is one of the most important characteristics of tool steel

and retained austenite itself is a phase present in the structure of many steels subjected to hardening treatment.

On the basis of data presents in work [1] one may assume that most significant factors are morphology and level of phase stabilization.

Disadvantageous influence of retained austenite morphology, according to [2], is revealed when the phase is present in a form of uneven distributed blocks (islands). Such areas, due to ease of

austenite deformation, are places where plastic strains are cumulating while other areas (with higher yield strength) may crack within elastic range – in brittle way. As a result of presence of austenite with such morphology a decrease of overall ductility of test material occurs. Moreover, in accordance with authors of work [1] and [3], retained austenite in island form poses higher inclination to mechanical and thermal destabilization, what may lead to relatively easy transformation into brittle martensite and finally to easy cracking through its brittle areas.

The authors of [1] emphasize that in certain cases "island" morphology of retained austenite apparently may be advantageous for fracture toughness of steel. In their opinion, austenite islands, as far as they remain thermally and mechanically stable, as a result of its ability to easy deformation may cause partial or total hindering of propagating crack through it, what should increase fracture toughness.

In comparison to improper morphology, lack of retained austenite stability, according to many researchers, turns out to be more unfavourable factor. Paper [4] points out to significantly detrimental influence of unstable (thermally) austenite on fracture toughness. One states, in the paper, that increased content of retained austenite in the structure of heat treated low-alloyed steels is major cause of their impact strength decrease. Similar conclusions was described in paper [5]. On the basis of impact resistance tests of X8Ni9 steel and fractographic observations of fractures from broken samples pre-cooled below the temperature of transition to brittle state, it was found distinct acceleration of brittle cracking through the areas of fracture which were identified as transformed austenite.

According to authors of paper [4] and [6] thermal instability of this phase and, as its consequence, easy disintegration to α phase and carbides during tempering may lead to creation of cementite layer on the boundaries between austenite and martensite strip, making brittle cracking easier. This fact according to many physical metallurgists is still considered as major cause of temper brittleness.

One may not rule out that in cases described there was occurring, due to intensity increase of applied stress close to the notch top, in test samples for impact strength, a mechanical destabilization of austenite what additionally would favour its transition into fresh and probably brittle martensite leading to decrease of fracture toughness within such areas.

According to [7], such adverse for fracture toughness result of presence of mechanically unstable retained austenite in the structure is particularly dangerous in tool steels. Progressive transition of mechanically unstable austenite into fresh martensite may result in stress increase in their volume and lead to initiation of cracks inside them.

The opinions presented above, unequivocally indicate that mechanically unstable retained austenite from the area of plastic strain zone, which is formed in front of propagating crack, would easily be transformed into fresh and brittle martensite decreasing fracture toughness. However there were also such works (among others [8-11]), which authors state that even unstable retained austenite, prior to transformation into fresh martensite, may obstruct crack development.

For the first time an advantageous influence of retained austenite on fracture toughness was pointed in works [12-14]. It was stated there that increase of retained austenite content properly distributed in the structure of a steel wouldn't only reduce the fracture toughness of these steels but strongly increase it.

These observations were confirmed afterwards during testing of tool steels [15, 16], where every 1% vol. of retained austenite would increase fracture toughness (K_{Ic}) by about 5%.

Quoted results of the research so far conducted indicate that major cause of discrepancies between opinions on the influence of retained austenite on fracture toughness of steel is its stability. Therefore in order to investigate the part played by retained austenite in cracking process one should apply heat treatment in a way allowing to avoid the transformation of this phase into mixture of ferrite and carbides or fresh martensite during tempering or further operating.

2. Testing material and its heat treatment

Chemical composition of steel selected for investigation is presented in Table 1.

Table 1.
Chemical composition of 70MnCrMoV9-2-4-2 steel

mass %									
C	Mn	Si	Cr	P	S	Mo	Ni	V	Fe
0.70	2.15	0.30	0.54	0.015	0.005	0.44	0.13	0.16	rest

All samples for testing were austenitized at 820°C for 30 minutes and after that, quenched in oil. The temperatures at which the steel samples were tempered (for 2 hours) were determined on the basis of knowledge of phase transformation kinetics during heating from hardened state which is described by CHT (Continuous Heating Transformations) diagrams [18-20].

Diagram of phase transformation kinetics during tempering for 70MnCrMoV9-2-4-2 steel was presented in Fig. 1. The following temperatures were selected: 120, 170, 220, 300, 350 and 400°C. In order to diversify the content of retained austenite in test samples some of them were subjected to cold treatment in liquid nitrogen (for 1 hour) after quenching. Each version of heat treatment was represented by 3 samples.

3. Testing methods used

- Hardness testing was conducted using Vickers apparatus of HP250 type with 30 kG load.
- Fracture toughness testing (stress intensity factor) was conducted with a method of linear-elastic fracture mechanics using INSTRON testing machine according to PN-EN ISO 12737. Samples were fractured with three-point bending method.
- Impact strength testing was conducted using 150J impact testing machine on samples with notch with a radius of 1 mm and 2 mm deep.
- Volumetric fraction of retained austenite determination was performed on cross sections of samples used for evaluation of K_{Ic} , after fracture electrosark cut off, grinding and polishing of the surface. Cobalt tube radiation was used - $Co_{K\alpha}$ recording 111_{γ} and 110_{α} reflections. Recording was conducted using PHILIPS-PW1710 diffractometer.
- Fractographic investigation was made using Stereoscan 120 scanning microscope with magnification of 500 and 2000x.

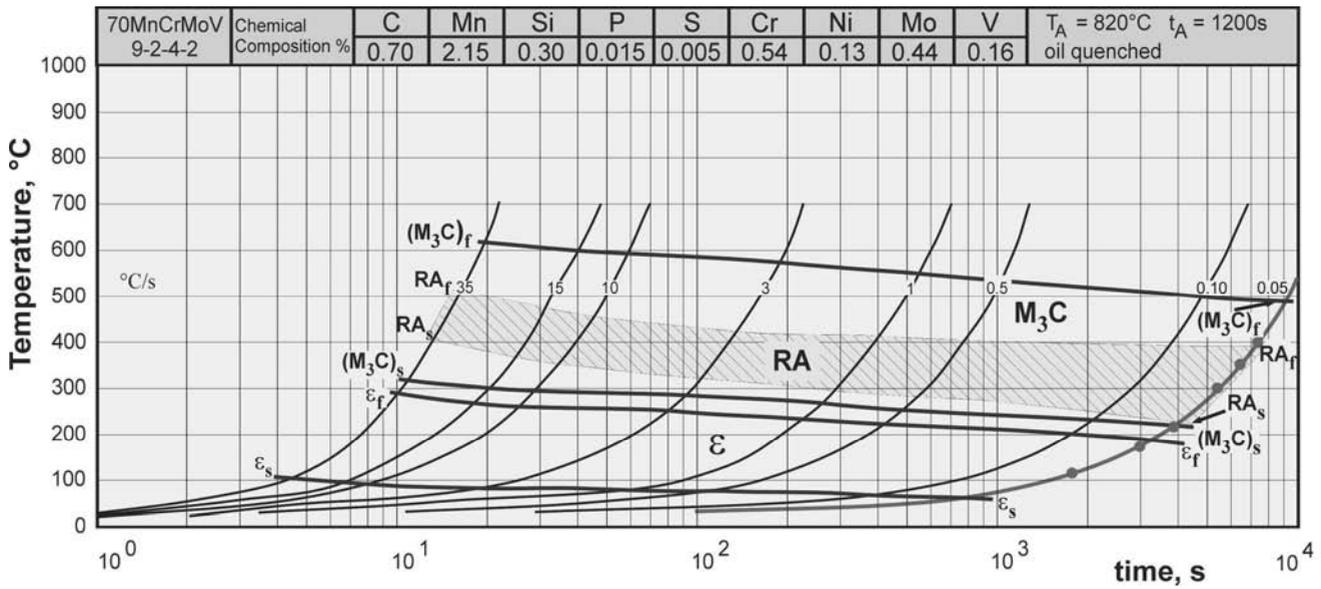


Fig. 1. Diagram of phase transformation kinetics during tempering for 70MnCrMoV9-2-4-2 steel, in acc. with [17]

4. Research results and discussion

Fig. 2 presents test results of influence of tempering temperature on hardness of tested steel samples, assigned for fracture toughness testing (K_{Ic}). Whereas Fig. 3 presents the influence of tempering temperature on retained austenite content in the same samples.

One may notice that along with the increase of tempering temperature the hardness of tested steel is decreasing. Cold treated samples keep higher hardness within whole range of temperatures what indicates that in the samples in result of cold treatment after quenching part of retained austenite has transformed into martensite. Up to 120°C (Fig. 2) no significant changes of tested steel are observed what indicates insignificant advance of transformations during tempering. Tempering in range of 20-120°C is accompanied by also insignificant changes of retained austenite content (compare Fig. 3). Fraction of this phase in samples not subjected to cold treatment drops by ca. 0.3% while in samples subjected to cold treatment by ca. 1.3%. However, no positive dilatometric effects were found, therefore on CHT diagram (fig.1) the transformation of retained austenite was not noted until temperatures above 220°C (for lowest rate of heating at 0.05°C/s).

After tempering at higher temperature i.e. at 170 and 220°C for both (cold treated and not) intensification of hardness decrease was observed (compare to Fig. 2). It would follow from CHT diagram in Fig. 1 that an effect of most intensive softening of tested steel may be corresponding to ϵ carbide precipitation. However, it is important to point out that according to Fig. 3 this intensification of softening between 120°C and 220°C is accompanied by increase in volume fraction of retained austenite what also would contribute to decreasing hardness of tested steel.

With tempering temperature increasing from 220°C to 300°C, slowing down of tendency for softening of 70MnCrMoV9-2-4-2

steel is observed. Simultaneously within the same temperature range (Fig. 3) sudden drop of the retained austenite fraction is observed, due to thermal destabilization of this phase (compare Fig. 1). Therefore, one may presume that final hardness of samples tempered at 300°C was influenced by two overlapping effects: hardness lowering precipitation of carbon excess from tempered martensite and thermal destabilization of soft retained austenite and its transition into fresh, hard martensite (or bainite).

Above 300°C, a repeated fast decrease of tested steel hardness is a result of alloy cementite precipitation as well as softening of previously formed low-tempered martensite (lower bainite).

Observed at 400°C a proximity of hardness change curves (compare Fig. 2) may indicate that in tested steel, at that temperature, there is present so intensive thermal destabilization of retained austenite that this phase no longer influences on the hardness of tested steel. These observations confirm the conclusions, from research of phase transformation kinetics during tempering of tested steel described in work [17], that at 400°C there are no distinct dilatation effects corresponding to retained austenite transition anymore (compare Fig. 1).

In Fig. 3 retained austenite fraction increase in a samples tempered at 170 and 220°C irrespective of whether they were cold treated or not. In samples without cold treatment applied there was, during tempering at 220°C compared to the samples tempered at 120°C, fraction increase of retained austenite at the average of ca. 5.4%. Whereas for analogically tempered samples after cold treatment the differences were even higher and were at the average of 6.1% vol.

Such high differences in fraction of retained austenite may not be explained by imperfection of X-ray method itself. It is also impossible to assign these differences to potential errors during metallographic sections preparation, because they were prepared with special care (compare chapter 3). Furthermore, as it comes from the research on mechanical destabilization of retained austenite in this steel, described

in work [21], the samples tempered at 120°C and 170°C were characterized by very high mechanical stability what practically excludes the possibility of its destabilization during incorrect polishing of metallographic sections.

The changes in fraction of retained austenite with tempering temperature observed shall not be considered as unexpected or surprising because similar changes have already been recorded during test and even for different grades of steel (compare works [22, 23]).

The results of research on the influence of tempering temperature on magnitude of stress intensity factor K_{Ic} of 70MnCrMoV9-2-4-2 steel are presented in Fig. 4. Whereas Fig. 5 presents the influence of tempering temperature on impact strength of tested steel, evaluated on similarly processed samples.

As one may notice, the character of K_{Ic} factor and KCU2 impact strength changes with tempering temperature is nearly alike. In both diagrams, within the whole tempering temperatures range, the fracture toughness of tested steel reaches local maximum after tempering at 220°C, while tempering at 300°C resulted in decrease of its fracture toughness to local minimum.

Since impact strength (work of breaking) is a sum of nucleation work and work of crack propagation, while K_{Ic} factor is a measure of steel resistance to cracks propagation only, one may state that it is a way of cracks propagation in the steel that determines the fracture toughness of 70MnCrMoV9-2-4-2 steel.

The cold treated samples (both for K_{Ic} and impact strength tests), with less amount of retained austenite, exhibited lower fracture toughness within the whole tempering temperatures interval.

This observation proves that remaining austenite left in the structure of 70MnCrMoV9-2-4-2 steel apart from its stability level, increases fracture toughness evaluated both with K_{Ic} factor and KCU2 impact strength test.

Analysis of changes of retained austenite fraction in samples from tested steel correlated with fracture toughness of these samples leads to very interesting conclusions. Such juxtapositions for stress intensity factor K_{Ic} are shown in Fig. 6 while for impact strength in Fig. 7.

It is easy to notice that apart from testing method of fracture toughness used the increase of tempering temperature from 120 to 220°C resulted in distinct, high increase of K_{Ic} factor as well as of KCU2 impact strength. Increase of fracture toughness observed within this range of temperatures has natural relationship to development of tempering processes and softening of the structure. However, one can notice, that in both figures increase of fracture toughness up to local maximum at 220°C is accompanied by increase of retained austenite fraction in the structure of test samples and even irrespective of whether they have been cold treated before tempering or not.

It is confirmed by previously proved fact that presence of retained austenite in the structure of tested steel increases its fracture toughness.

However, it is worth to notice (Fig. 4-7) that during tempering at 300°C, fracture toughness of the samples reached local minimum, and there was found a significant decrease of retained austenite fraction in the structure of the samples. Besides, cold treatment in liquid nitrogen turned out to be meaningless because decrease of fraction of retained austenite occurred in both cases of samples i.e. with cold treatment as well as without it and in both types of samples it was accompanied by decrease of fracture toughness.

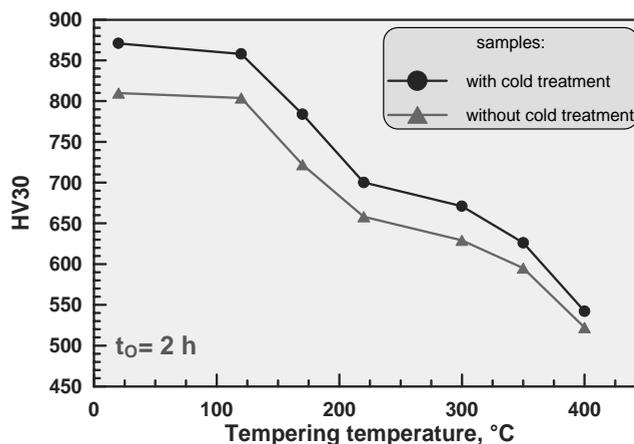


Fig. 2. Influence of tempering temperature on hardness HV30 of tested steel after hardening from 820°

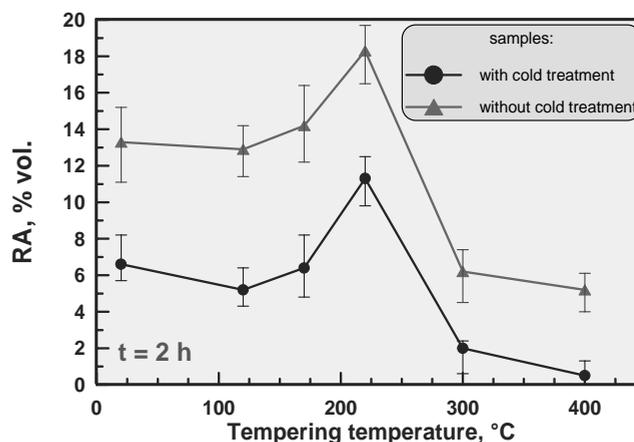


Fig. 3. Influence of tempering temperature on volume fraction of retained austenite in 70MnCrMoV9-2-4-2 steel quenched from 820°C

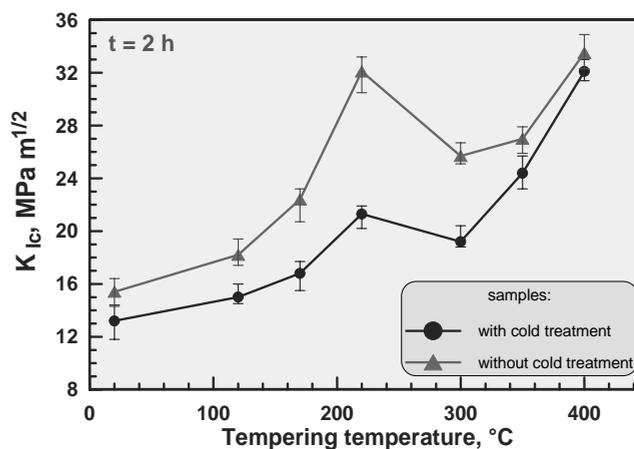


Fig. 4. Influence of tempering temperature on changes of stress intensity factor K_{Ic} of 70MnCrMoV9-2-4-2 steel

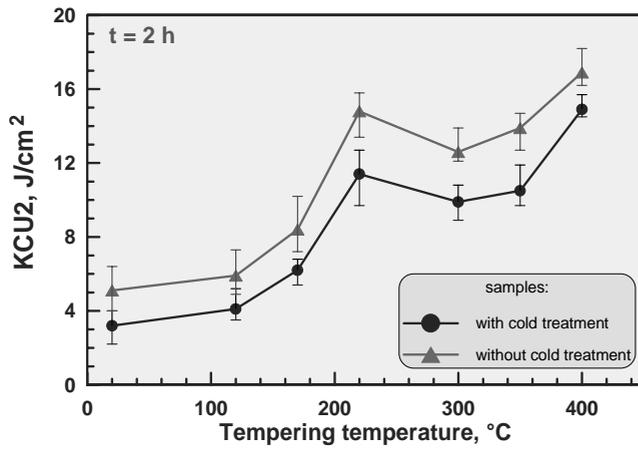


Fig. 5. Influence of tempering temperature on impact strength KCU2 of 70MnCrMoV9-2-4-2 steel

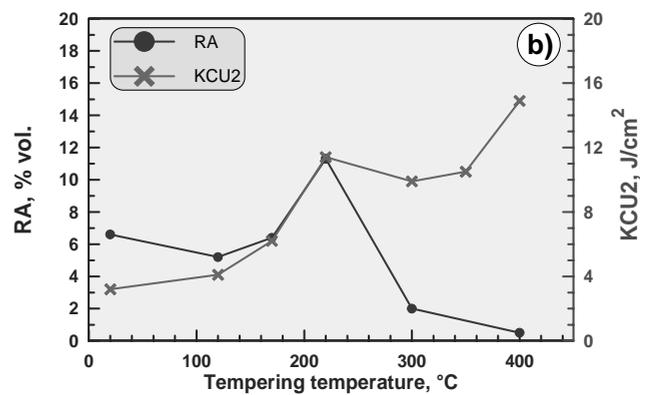
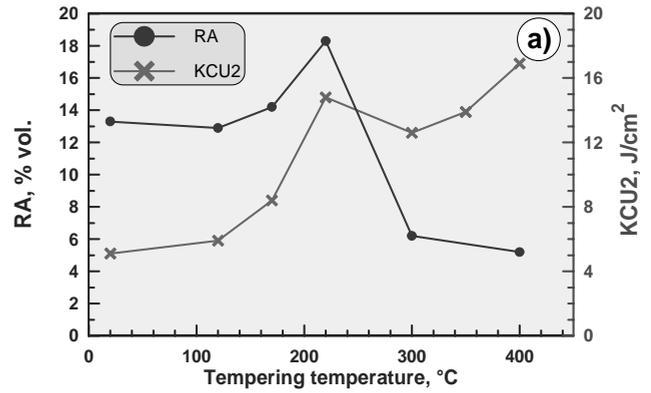


Fig. 7. Influence of tempering temperature on impact strength (KCU2) and volume fraction of retained austenite (% vol.) in quenched from 820°C steel 70MnCrMoV9-2-4-2 in state: a) without cold treatment; b) after cold treatment at -196°C

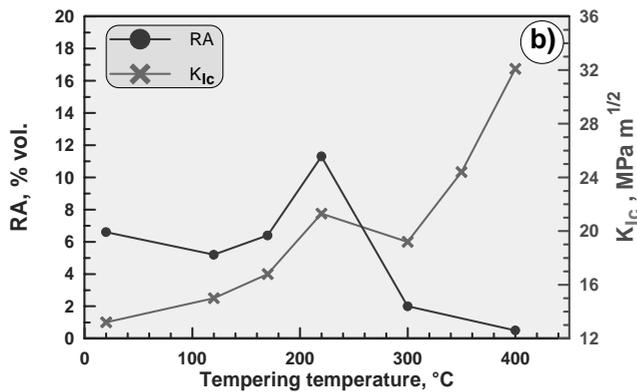
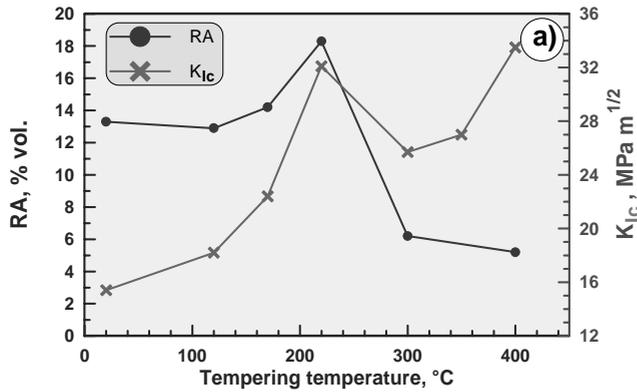


Fig. 6. Influence of tempering temperature on stress intensity factor (K_{Ic}) and on volume fraction of retained austenite (% vol.) in quenched from 820°C steel 70MnCrMoV9-2-4-2 in state: a) without cold treatment; b) after cold treatment at -196°C

Following from the Table 2, relative decrease of fracture toughness due to rising the temperature of tempering from 220 to 300°C is the stronger the greater is decrease of retained austenite fraction. It is particularly important when changes of fracture toughness are evaluated using K_{Ic} factor. Therefore one may suppose that, in spite of proven profitable influence of retained austenite presence to fracture toughness, its thermal destabilization at 300°C may be one of the reasons why a phenomenon of temper brittleness of the first type occurs.

Table 2.

Changes of fraction of retained austenite (ΔRA) and the changes of fracture toughness (ΔK_{Ic} and $\Delta KCU2$) of 70MnCrMoV9-2-4-2 steel after rising the tempering temperature from 220 up to 300°C

Samples without cold treatment				
ΔRA	ΔK_{Ic}		$\Delta KCU2$	
[%]	[MPa·m ^{1/2}]	[%]	[J/cm ²]	[%]
12.1	6.4	19.9	2.2	14.9
Samples with cold treatment				
ΔRA	ΔK_{Ic}		$\Delta KCU2$	
[%]	[MPa·m ^{1/2}]	[%]	[J/cm ²]	[%]
9.3	2.1	9.9	1.5	13.2

One should not forget, in accordance with the opinions expressed among others in works [24, 25], that main cause for temper brittleness may be solution of ϵ carbide and redistribution of carbon not only to sites of stable phase nucleation (cementite) but also to dislocation tangles determining e.g. boundaries of cellular structure. Thus it is possible with high probability to assume that after tempering of tested steel above 220°C a true decrease of fracture toughness, following from $\epsilon \rightarrow M_3C$ transition, would be even greater if present in the structure retained austenite did not hinder this tendency.

Increase of tempering temperature above 300°C, shown in fig. 4-7, results in gradual increase of fracture toughness of tested steel. Yet at these temperatures about the ductility of tested steel a progressing process of martensite tempering is decisive. Although there is still a little amount of retained austenite left in the samples tempered so high but its advantageous influence on ductility of tested steel becomes smaller and smaller.

Fig. 8-11 present pictures recorded using scanning microscope of selected fractures of samples used for K_{Ic} factor determination after their quenching from 820°C (cold treatment at -196°C if needed) and tempering at 120, 220, 300 and 400°C. The differences in type of fracture were found only for samples tempered at 120 and 220°C (compare Fig. 8 and 9). It is important to record that exactly at these temperatures the greatest differences in retained austenite

fractions occurred in the samples that were cold treated and the ones without such treatment applied (compare Fig.3).

One may notice, in the photographs shown, that increase of tempering temperature from 120°C to 220°C caused distinct growth fraction of fractures with ductile-well character. One may assume that the wells are the result of microvoids round ϵ carbide precipitations and retained austenite present in the matrix might have foster a creation of such fracture.

After tempering at 300°C, when fracture toughness of tested steel reaches local minimum (compare Fig. 4-7) for both type of samples the fracture becomes brittle (quasi-fissile) and it possess numerous secondary cracks (compare Fig. 10). Such character of fracture may indicate the loss of favourable influence of retained austenite, which fraction strongly drops (in case of samples without cold treatment to about 6% vol., while in cold treated samples to about 2% vol.) and its place takes fresh and brittle martensite what is mentioned among others in papers [4, 5, 6]. Such fracture, however, may also be a result of mentioned before changes which take place in ferritic part of matrix of tested steel during solution of ϵ carbide preceding cementite creation.

Rise of tempering temperature to 400°C resulted in restoration of fracture with ductile-well character (compare Fig. 11), yet in this case most probably there are the cementite particles precipitated in wells.

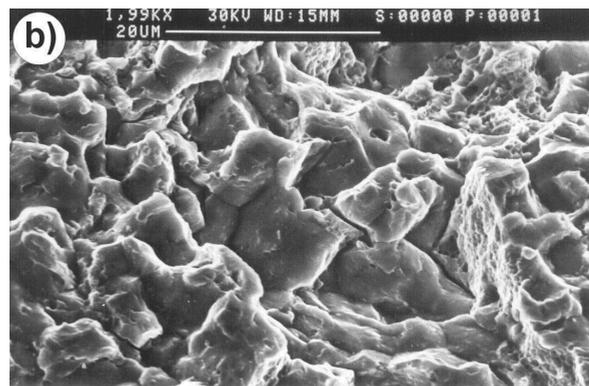
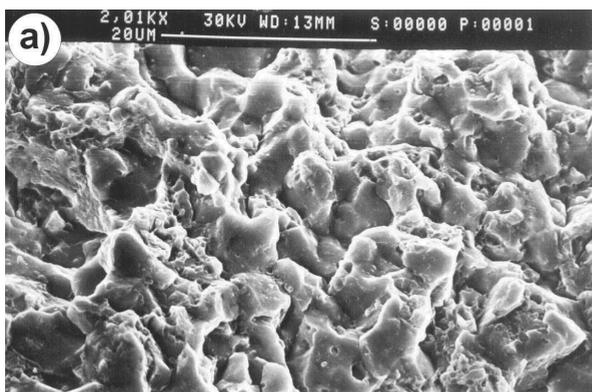


Fig. 8. Character of fractures of samples used for determination of K_{Ic} factor of 70MnCrMoV9-2-4-2 steel after quenching from 820°C and tempering at 120°C: a) samples without cold treatment: %RA = 12.9%; K_{Ic} = 18.2 MPa·m^{1/2}; KCU2 = 5.9 J/cm²; 804 HV30, b) samples with cold treatment: %RA = 5.2%; K_{Ic} = 15.0 MPa·m^{1/2}; KCU2 = 4.1 J/cm²; 858 HV30

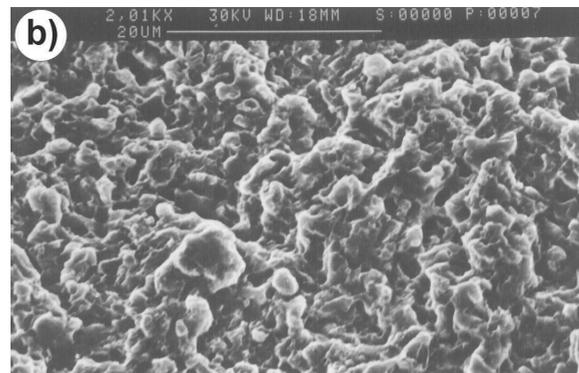
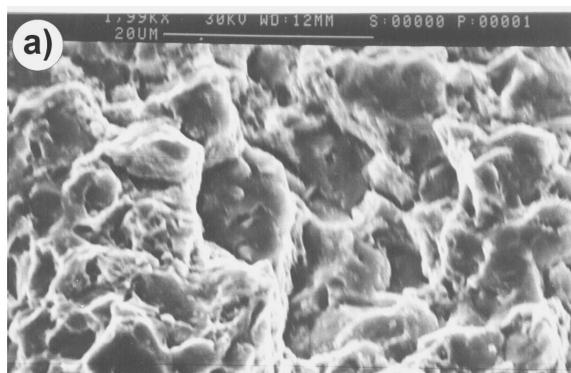


Fig. 9. Character of fractures of samples used for determination of K_{Ic} factor of 70MnCrMoV9-2-4-2 steel after quenching from 820°C and tempering at 220°C: a) samples without cold treatment: %RA = 18.3%; K_{Ic} = 32.1 MPa·m^{1/2}; KCU2 = 14.8 J/cm²; 658 HV30, b) samples with cold treatment: %RA = 11.3%; K_{Ic} = 21.3 MPa·m^{1/2}; KCU2 = 11.4 J/cm²; 700 HV30

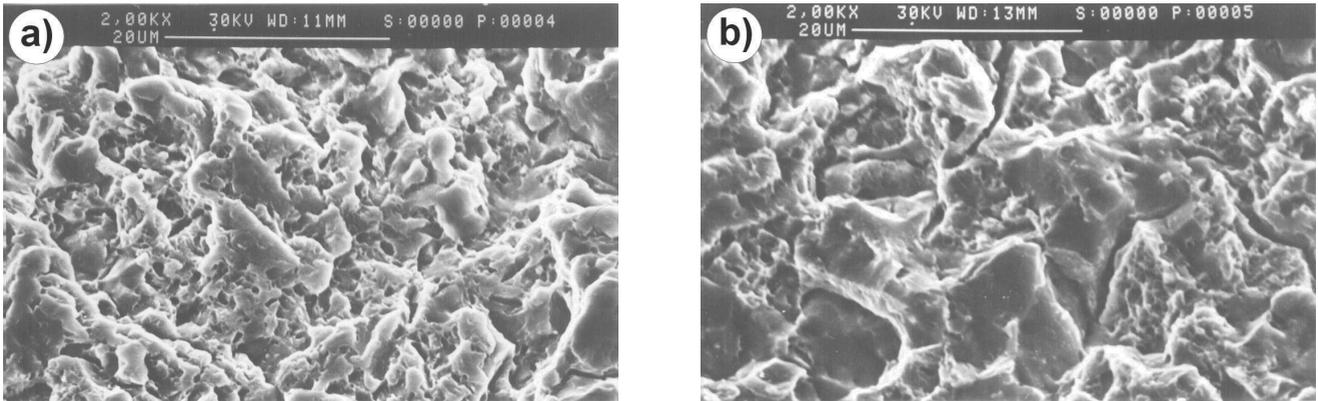


Fig. 10. Character of fractures of samples used for determination of K_{Ic} factor of 70MnCrMoV9-2-4-2 steel after quenching from 820°C and tempering at 300°C: a) samples without cold treatment: %RA = 6.2%; K_{Ic} = 25.7 MPa•m^{1/2}; KCU2 = 12.6 J/cm²; 629 HV30, b) samples with cold treatment: %RA = 2.0%; K_{Ic} = 19.2 MPa•m^{1/2}; KCU2 = 9.9 J/cm²; 671 HV30

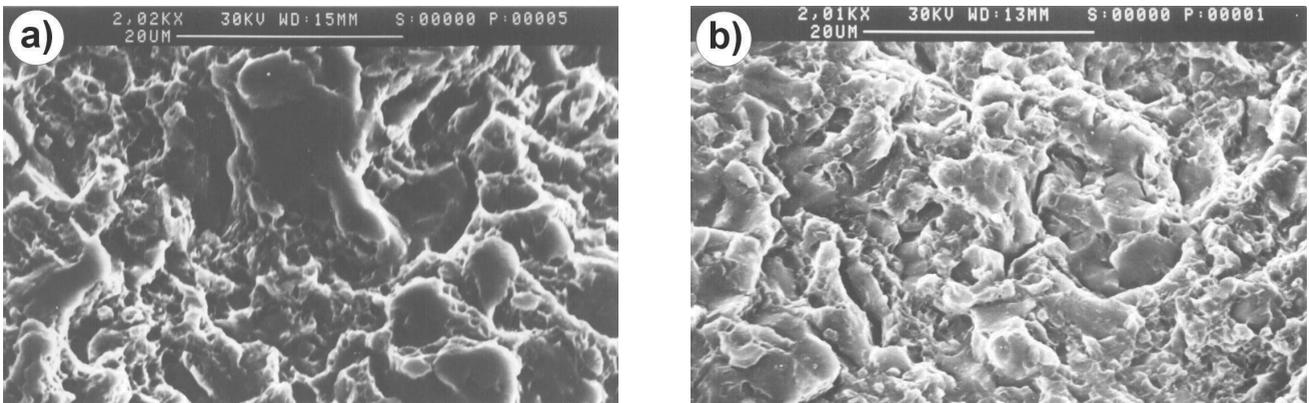


Fig.11. Character of fractures of samples used for determination of K_{Ic} factor of 70MnCrMoV9-2-4-2 steel after quenching from 820°C and tempering at 400°C: a) samples without cold treatment: %RA = 5.2%; K_{Ic} = 33.5 MPa•m^{1/2}; KCU2 = 16.9 J/cm²; 522 HV30, b) samples with cold treatment: %RA = 0.5%; K_{Ic} = 32.1 MPa•m^{1/2}; KCU2 = 14.9 J/cm²; 542 HV30

5. Conclusions

The results of investigation concerning relations between fraction of retained austenite, tempering temperature, hardness and fracture toughness presented in this paper may enrich and complement the knowledge about the part played by this phase in steel cracking process. The research conducted and results analysis makes it possible to formulate the following conclusions:

1. Retained austenite remaining in the structure of 70MnCrMoV9-2-4-2 steel quenched from 820°C increased its fracture toughness proportionally to its content. Such advantageous influence of this phase was also found after tempering tested steel at temperatures within the range of 120-400°C.
2. After tempering tested steel at 120°C no distinct changes in fraction of retained austenite in comparison with hardened state were observed. Simultaneously, it was found that such low tempering results in very strong stabilization of the phase. For this reason, from selection of optimal technology of heat treatment, the temperature may be recognized as optimal for tempering of 70MnCrMoV9-2-4-2 steel.
3. Retained austenite present in samples of tested steel, which were tempered, after quenching, at the temperatures within the range of 220-400°C, was subject to thermal destabilization and was transforming into fresh martensite (or bainite). Since it was found that such transition of austenite was accompanied by decrease of fracture toughness of tested steel, therefore it is recommended to temper tools made of tested steel at the temperature not higher than 220°C.
4. Phenomenon of temper brittleness of first type found in 70MnCrMoV9-2-4-2 steel may be at least partially related to thermal destabilization of retained austenite and its transition into martensite or bainite. However, research results presented in this paper let hope that know-how of such heat treatment, which would make possible to stabilize this phase in the structure of hardened steels, would contribute not only to restrain temper brittleness but even to complete elimination of this adverse phenomenon, if the structure contained adequate amount of stable retained austenite.

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