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EFFECT OF CARBON CONTENT ON THE FRACTURE TOUGHNESS OF Ni-Cr-Mo STEELS

WPŁYW WĘGLA NA ODPORNOŚĆ NA PĘKANIE STALI Ni-Cr-Mo

In this paper the effect of carbon content on the fracture toughness changes with tempering temperature of three Ni-Cr-Mo steels containing so-called strong „background" of other alloying elements is presented. The effect of tempering temperature on the steels' toughness was examined by the linear elastic fracture mechanics (K_{Ic} test). It was demonstrated that alloys containing 0.10 and 0.31% C are characterized by high fracture toughness and low ability to irreversible embrittlement after low – temperature tempering. The alloy containing 0.79% C is characterized by the lowest fracture toughness within the whole range of tempering temperature. Mechanical investigations were also supplemented with fracture surfaces observations.

The obtained results are supposed to complement the existing software and d-bases pertaining to the quantitative effect of elements on steels' properties.

Keywords: Ni-Cr-Mo steel, fracture toughness (K_{Ic}), irreversible embrittlement, fractographic examination

W pracy przedstawiono wyniki badań wpływu węgla na zmiany odporności na pękanie z temperaturą odpuszczania trzech stopów modelowych stali Ni-Cr-Mo zawierających tzw. silne „tło" innych pierwiastków stopowych. Zmiany odporności na pękanie stopów z temperaturą odpuszczania określono metodą liniowo – sprężystej mechaniki pękania (przez pomiar współczynnika intensywności naprężeń K_{Ic}). Wykazano, że stopy zawierające 0,10 i 0,31% C charakteryzują się bardzo dobrą odpornością na pękanie i małą wrażliwością na kruchość odpuszczania I rodzaju po niskim odpuszczaniu. Najmniejszą odpornością na pękanie w całym zakresie temperatur odpuszczania cechuje się stop zawierający 0,79% C. Badania mechaniczne dodatkowo poparto dokumentacją fraktograficzną przełomów próbek.

Wyniki badań uzyskane w niniejszej pracy z pewnością uzupełnią istniejące już programy komputerowe oraz bazy danych dotyczące ilościowego wpływu pierwiastków stopowych na własności stali.

1. Introduction

The qualitative and quantitative influence of carbon content on mechanical properties (including fracture toughness) of different types of steel has a great importance for designing of a proper technology of their heat treatment. Increase of carbon content in steels increases their strength, simultaneously lowering weldability and fracture toughness. Furthermore, carbon strongly lowers the martensite start temperature Ms, increasing the risk of creation of hardening cracks in steel [1].

When designing the technology of steel, heat treatment in a temperature range of (250÷350°C), when an irreversible embrittlement occurs should be avoided. Decrease of fracture toughness of steels tempered within this range of temperatures may come from destabilization of retained austenite, non-uniform disintegration of martensite (favored along grain boundaries of former austenite), segregation of undesirable impurities (As, Sn, P, Sb) towards interfacial boundaries [2] as well as cementite precipitation on boundaries of martensite strips [3]. The Ref. [3] also shows that within the temperature range a redistribution of carbon in the matrix of tempered steel may occur as a result of solubilisation of metastable carbide ε. This may lead to local significant enrichment of the matrix with carbon causing a decrease of fracture toughness of the steel.

Quantitative evaluation of the carbon content influence on mechanical properties (including fracture toughness) of structural and tool steels was the objective of the researches in Ref. [4-9]. The evaluation has been performed on specially designed model alloys of steel containing manganese, silicon, chromium, vanadium and nickel.

In order to complement the data from Ref. [4-9] within the frames of this work it has been attempted to quantitatively evaluate the influence of carbon content from the range of 0.10÷0.79% on fracture toughness (expressed by stress intensity factor K_{Ic} in a static bending test) of Ni-Cr-Mo steels quenched from the range of

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homogenous austenite, and subsequently tempered with irreversible embrittlement taken into account.

2. Research materials

Three Ni-Cr-Mo steels with various carbon content, i.e. 0.10; 0.31 and 0.79% and similar content of other alloying elements were selected for testing.

The alloys were prepared in open induction furnace in Foundry Institute in Cracow. Ingots of test steels (with a mass of about 30 kg and diameter of about 150 mm), were reforged into bars with a cross section of 20×35 mm. Chemical compositions of the Ni-Cr-Mo steels are presented in Table 1.

TABLE

Chemical composition of the Ni-Cr-Mo steels (% by mass)

Steel no.	% C	% Si	% Mn	% P	% S	% Cr	% Ni	% Cu	% Mo	% Al
1	0.10	0.17	0.70	0.012	0.012	1.50	2.60	0.09	0.40	0.01
2	0.31	0.15	0.73	0.008	0.016	1.59	2.50	0.03	0.35	0.03
3	0.79	0.21	0.84	0.025	0.020	1.60	2.45	0.11	0.43	0.03

3. Experimental procedure

The influence of carbon content from the range of 0.10 0.79% on the change of fracture toughness along with tempering temperature of the Ni-Cr-Mo steels has been evaluated from a bending test.

Steels samples were austenitized before the test for 30 minutes at following temperatures:

850°C, i.e. Ac_3 + 50°C – for steel no. 1 (0.10% C),
800°C, i.e. Ac_3 + 50°C – for steel no. 2 (0.31% C),
920°C, i.e. Ac_m + 50°C - for steel no. 3 (0.79% C)

and then quenched in oil. Quenched samples (with dimensions 15×30×140 mm) were then tempered at temperatures of: 200, 250, 350 and 600°C for 2 hours.

Austenitizing and tempering treatment were performed in Carbolite laboratory furnace of RHF 1600 type.

Each sample had mechanically made notch with a 2 mm deep fatigue crack at the bottom according to the procedure described in PN-EN ISO 12737. The samples were subjected to a three point bending test on an Instron testing machine. The change of bending force as a function of notch edge divergence was recorded. On the basis on recorded diagrams, K_{Ic} factors were determined.

Fractographic study was performed on fracture surfaces of samples used for determination of stress intensity factor K_{Ic}. Observations of the fractures were made by a Cambridge Stereoscan scanning microscope, with magnification of 1000 ×.

4. Results and discussion

Figure 1 presents results of KCU2 impact toughness tests performed in the work [9]. The graph illustrates the dependence of KCU2 on the tempering temperature of the Ni-Cr-Mo steels with diversified carbon content. It is known [10] that impact toughness is a measure of the resistance to nucleation and propagation of a crack.

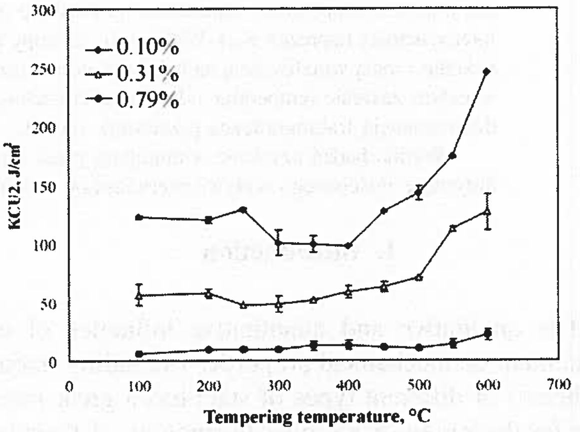

Fig. 1. Dependence of impact toughness (KCU2) on tempering temperature of steels with variable carbon concentration, acc. to [9]

Analysis of data presented in Figure 1 indicates that increase of carbon content within the range of 0.10÷0.79% results in the decrease of impact toughness within the whole range of tempering temperatures [9].

Steels no. 1 and 2 containing 0.10 and 0.31% of carbon respectively are susceptible to irreversible embrittlement. The increase of carbon content to 0.31% in the steel no 2 lowers the temperature of decrease of impact toughness corresponding to this embrittlement from 250 to 200°C.

Impact toughness of both steels (no. 1 and 2) within the range of tempering temperatures up to 200°C is relatively high and essentially remains on a constant level. Different characteristics of impact toughness changes against the tempering temperature is represented by steel no. 3 (0.79%). Within the whole range of test temperatures, the values of impact toughness are lower than for steels no. 1 and no. 2, i.e. from 8 J/cm^2 (at 100°C) up to 20 J/cm^2 (at 600°C).

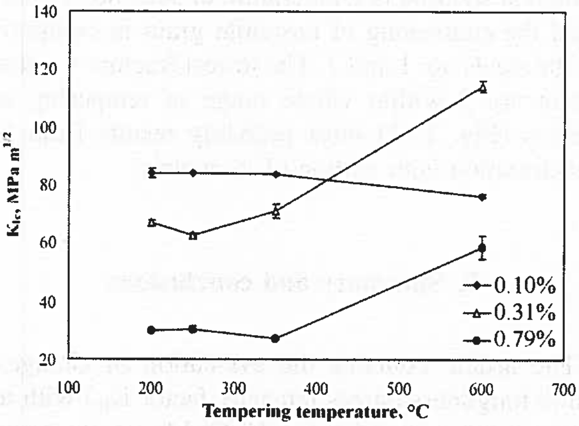

Fig. 2. Dependence of stress intensity factor (K_{Ic}) on tempering temperature of steels with variable carbon concentration

Figure 2 presents the changes of stress intensity factor K_{Ic} with tempering temperature of the Ni-Cr-Mo steels with a variable carbon concentration.

The K_{Ic} factor is a measure of resistance to propagation of cracks. As one can see the diversification of resistance to cracks propagation (K_{Ic}) is similar to the changes of impact toughness up to tempering temperature of 350°C. Within this range of tempering temperatures the increase of carbon content results in lowering of K_{Ic}. After tempering at 600°C the value of stress intensity factor of medium-carbon (0.31% C) and high-carbon (0.79% C) steel increases, while that one in the lowest-carbon steel (0.10% C) decreases. This information should be complemented though with a fact that it is here about the resistance to cracking propagation only and that for the steel containing 0.10% C after tempering at 600°C, the stress intensity factor is not a value of K_{Ic} but K_c, because the condition of plain strain had not been met during the test.

In the case of the lowest-carbon (0.10%) steel (no. 1), within the range of tempering temperatures 200 350°C (Fig. 2), the values of the K_{Ic} factor remain practically at the same level. In the case of the steel containing 0.31% of carbon at the temperature of 250°C, a minimum of K_{Ic} is observed. Definitely, the lowest values of stress intensity factor (the lowest resistance to cracks' propagation) within whole range of tempering temperatures have been recorded for the steel no. 3 (0.79% C). There is a slightly marked minimum of K_{Ic} existing at tempering temperature of 350°C in the steel.

In order to make the interpretation of the obtained results of fracture toughness tests easier the fractographic tests have been performed on fractures of samples for determination of stress intensity factor K_{Ic}. These test are complementary to evaluation of carbon content and tempering temperature influence on fracture toughness of the examinated steels.

Figures 3÷5 present the fractures of samples of the Ni-Cr-Mo steels tempered at different temperatures and subjected to fracture toughness measurements.

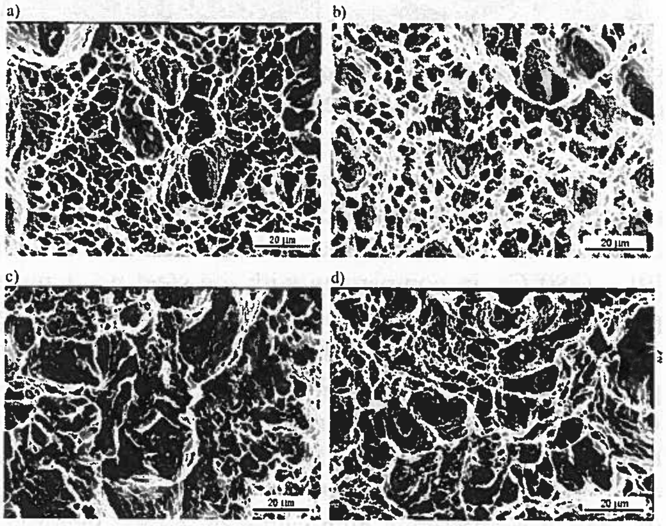

Fig. 3. Fracture surfaces of steel no. 1 (0.10% C), for different tempering temperatures (SEM): (a) 200°C, (b) 250°C, (c) 350°C, (d) 600°C

In the case of the steel containing 0.10% of carbon, after tempering at the temperature of 200 and 250°C, a ductile dimple fracture is observed (Fig. 3a, b). Tempering at 350°C causes a change in fracture character to the mixed one i.e. ductile dimple (with „island" character) and transgranular brittle (Fig. 3c). The emerging of transgranular brittle fracture is likely associated with the inter-strip precipitates of cementite. The cementite in steel no. 1, as was shown in work [9], precipitates in the temperature range of 200 350÷C. High fracture toughness of the steel after tempering at 350°C (apart from the presence of partially brittle fracture) may be a result of high fracture toughness of the matrix itself (which is advantageously influenced by the low carbon content as well as the high content of nickel). After tempering at 600°C the presence of ductile fracture with dimple character is observed again in spite of the fact that fracture toughness (K_{Ic}) insignificantly decreases (Fig. 3d).

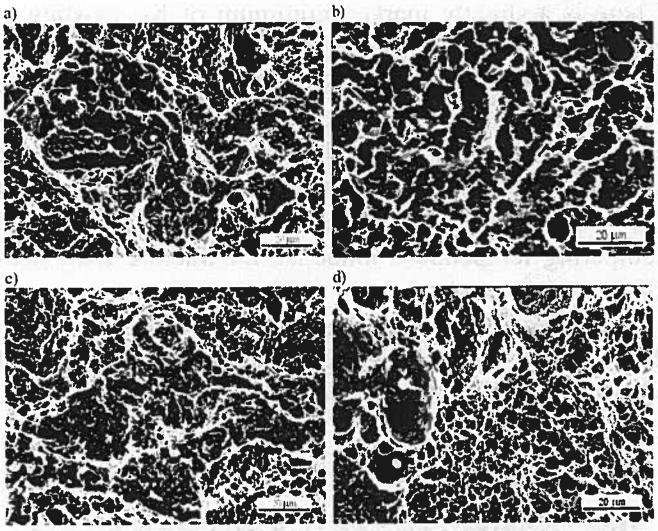

Fig. 4. Fracture surfaces of steel no. 2 (0.31% C), for different tempering temperatures (SEM): (a) 200°C, (b) 250°C, (c) 350°C, (d) 600°C

The steel no. 2 (0.31% of carbon) exhibits a little different character of fracture than steel no. 1. Lower martensite start temperature Ms in the steel, acc. to [9] – (280°C), in comparison with the steel no. 1 most probably has significantly limited the self-tempering of martensite. Most intensive quasi-brittle fracture is present after tempering at 250°C (Fig. 4b) and this is when the lowest fracture toughness of the test steel has been found (Fig. 2). Starting from tempering temperature of 350°C the fracture becomes ductile dimple (Fig. 4c, d), what is expressed in high values of the K_{Ic} factor after tempering of this alloy at the mentioned temperatures (Fig. 2).

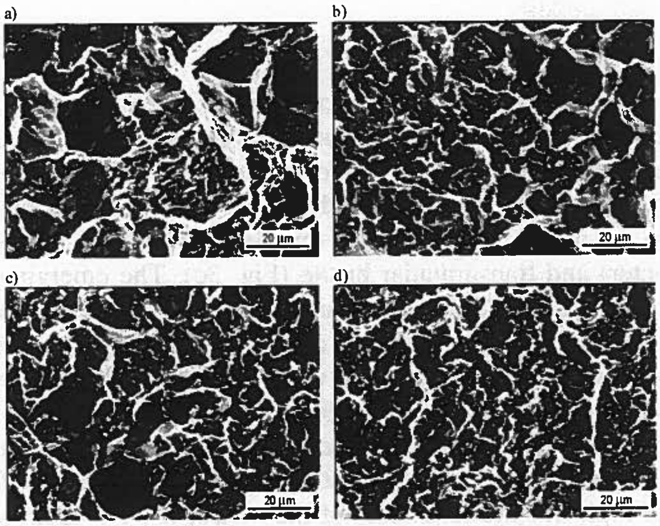

Fig. 5. Fracture surfaces of steel no. 3 (0.79% C), for different tempering temperatures (SEM): (a) 200°C, (b) 250°C, (c) 350°C, (d) 600°C

Different character of fractures along is exhibited by the highest-carbon (0.79%) steel no. 3. In samples tempered within the temperature range of 200÷250°C, a presence of high fraction of transcrystalline fracture is observed (Fig. 5a, b). It is most probably a result of secondary cementite precipitation along grain boundaries of former austenite. After tempering at 350 and 600°C the fracture becomes quasi-brittle (Fig. 5c, d) while the fracture toughness (K_{Ic}) to increase. It is worth noting that high austenitizing temperature of steel no. 3 (920°C) caused the coarsening of austenite grain in comparison with the steels no. 1 and 2. The lowest fracture toughness of steel no. 3 within whole range of tempering temperatures (Fig. 1, 2) most probably results from high supersaturation with carbon of its matrix.

5. Summary and conclusions

The article contains the evaluation of changes in fracture toughness (stress intensity factor K_{Ic}) with tempering temperature of three Ni-Cr-Mo steels containing diversified carbon content (0.10÷0.79%) and similar background of other alloying elements. Results of fracture toughness tests of the steels tempered at 200, 250, 350 and 600°C have been complemented with fractographic documentation of the fracture surfaces.

The obtained results allowed us to formulate the following conclusions:

- steels containing 0.10 and 0.31% of carbon are characterized by good fracture toughness even after low-temperature tempering. They are weakly sensitive to irreversible embrittlement,
- in the steel containing 0.10% of carbon the fracture is ductile dimple and only after tempering at 350°C a partial presence of transgranular clearage fracture is observed. Along with change of carbon content up to 0.31% there is a change of fracture character, which gradually becomes quasi-brittle,
- high fracture toughness of steels containing 0.10 and 0.31% of carbon may result from good properties of the matrix, which is advantageously influenced by low content of carbon and high content of nickel,
- the lowest fracture toughness within whole range of tempering temperatures is characteristic for the steel containing 0.79% of carbon. The lowest values of K_{Ic} and KCU2 of steel are most likely a result of high austenitizing temperature (920°C) and high supersaturation with carbon of its matrix. The justification of low fracture toughness of this alloy is supported by a character of fractures observed, which after tempering at the temperatures of 200 and 250°C are significantly transgranular and not until 350°C they become quasi-brittle.

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