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Influence of Fracture Toughness on Vacuum Hardened HSS

Vpliv lomne žilavosti na vakuumsko toplotno obdelano hitrorezno jeklo

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Fractures, macro-chipping and micro-chipping are all effects by which cutting edges are destroyed. The ability of a steel to resist these phenomena is known as its toughness. HSS, however, possess an appreciable ductility, although the notched or even unnotched specimens tested in the pendulum test are not sensitive enough to discriminate between high and low levels of toughness. Therefore, it becomes important to use a method of testing which can detect small variations in ductility. To establish the fracture toughness, the round-notched tensile specimens with a fatigue crack at the notch root was used. Fatiguing was done in as soft annealed condition. After that, the vacuum heat treatment for the achievement of optimal working properties was carried out and the final testing was performed. Our experiments confirm that the correlation based on the round-notched tension test can be successfully used to calculate the critical fracture toughness. On the basis of the above-mentioned experimental results, we were able to compose a diagram which simultaneously scoops the technological parameters of vacuum heat-treatment, the mechanical properties and the micro structure of vacuum heat-treated HSS M2.

Key words: fine blanking tool, fracture toughness, hardness, vacuum heat treatment

Lomi, makrookruški in mikrookruški so vzrok propadanja rezilnih robov. Sposobnost jekla, da se upira tem pojavom, pa je poznana kot žilavost. Hitrorezno jeklo ima upoštevanja vredno duktilnost, četudi preizkušanci z zarezo ali celo celo brez zareze pri Charpyjevem preizkusu niso dovolj selektivni, da bi nam omogočali določitev krhke oz. žilave narave loma. Za krhke materiale, med katere spada hitrorezno jeklo, je pomembno, da izberemo metodo preizkušanja, ki zazna že majhne spremembe duktilnosti jekla ter je selektivna in reproduktivna. Poleg standardnega načina merjenja lomne žilavosti na preizkušancih, ki so dovolj debeli, da je izpolnjen pogoj ravninskega deformacijskega stanja, uporabljamo tudi nestandardni način merjenja lomne žilavosti, s cilindričnimi nateznimi preizkušanci z zarezo po obodu. Problemi pri ustvarjanju razpoke v korenu zareze, so nas navedli na idejo, da metodo za določevanje lomne žilavosti s pomočjo cilindričnih preizkušancev z zarezo po obodu modificiramo. Doseženi rezultati so pokazali, da je modificirana metoda tudi dovolj selektivna. Osnovni namen modifikacije je, ustvariti razpoko kontrolirane globine v korenu zareze na mehko žarjenih cilindričnih preizkušancih z zarezo po obodu. Predpulzirane cilindrične preizkušance zatem vakuumsko toplotno obdelamo, temu pa sledi natezni preizkus. Na osnovi rezultatov dobljenih s pomočjo modificirane metode, smo uspeli na istem diagramu zajeti mehanske lastnosti, tehnološke parametre vakuumske toplotne obdelave in mikrostrukturo vakuumsko toplotno obdelanih preizkušancev iz hitroreznega jekla M2.

Ključne besede: orodje za precizno štancanje, lomna žilavost, trdota, vakuumska toplotna obdelava

1. Introduction

A carefully selected vacuum heat treatment process improves the basic characteristics of HSS M2. The required working hardness and fracture toughness of HSS is determined mainly by the hardening and tempering temperatures, depending on the alloying1. With the optimal vacuum heat treatment process, the best possible combination of fracture toughness and hardness, and therefore, wear resistance, is reached.

The design calculations of HSS tools must consider the material strength, with a special emphasis on fracture toughness, because of the danger of brittle tool fracture. Fracture toughness is defined as the ability of a material under stress to resist the propagation of a sharp crack. To establish the fracture toughness of HSS in hardened and tempered conditions, a non-standard testing method with small-scale specimens was developed. This method involves the introduction of a sharp crack at the notch root, in our case, by pulsating round-notched tension specimens, thermal treatment and tensile testing. A high level of hardness makes round specimens

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greatly sensitive to notches, so the test can fail due to unsuccessful pulsating. When successful prepulsating, a fatigue crack is performed at the notch root of the specimen. The method was modified with the formation of a circumferential crack of defined depth at the root of the machined notch on soft annealing specimens, than a tensile test was performed after vacuum heat treatment. Our experiments confirm that the measurements based on the modified round-notched tension test can be successfully used to determine the fracture toughness.

2. Basic characteristics of high speed tool steel M2

Due to the higher wear resistance of HSS, they are nowadays used also for fine blanking, cold working and deep drawing tools, especially in long series. Tool steels must withstand compressive stresses and abrasive or adhesive wear, while have a sufficient toughness to resist chipping and failure. HSS have better resistance to wear in comparison to cold work tool steels because of the increased hardness of the matrix, and of the carbide phase.

The carbide phase in the matrix of HSS increases the wear resistance which is relative to the total volume of carbides, and also to their hardness. The wear resistance in HSS is mainly determined by vanadium carbides which have a micro-hardness of 2200 to 2400 HV[2,3], **(Fig. 1).**

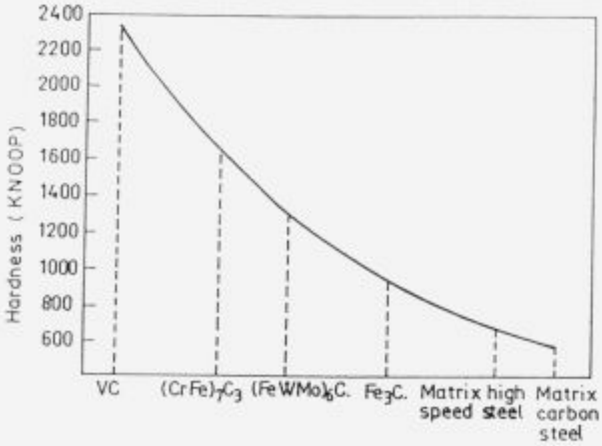


Figure 1: The comparative hardness of carbides found in tool steels2

Slika 1: Primerjalne vrednosti trdot karbidov, ki jih najdemo v hitroreznih jeklih

However, it must not be forgotten that HSS have a greater hot hardness. Even if the work pieces are place into the tools while cold, the working tool surfaces become hot.

Fractures, macro-chipping and micro-chipping can destroy the cutting edges. The ability of a steel to resist these phenomena is known as toughness. The toughness that can be achieved by HSS is limited by the defects in the steel (carbide segregations and bands inclusions etc.). When the steel is subjected to a load, stress concentrations can appear around the defects and cause a tool fracture, unless the stress concentrations are relieved by a local plastic flow on the micro scale. The ability of the matrix to undergo plastic flow can be altered within wide limits by varying the hardness. Thus, the defects in the steel determine the maximum toughness which can be achieved. On the other hand, the heat treatment determines the toughness degree actually achieved within the limits set by the defects.

Vacuum heat treatment is one of the most important operations in the manufacturing of tools. Therefore, when HSS are used for cold working processes, the situation is met by choosing low hardening temperatures and tempering temperatures below the peak secondary hardening temperature, to improve fracture toughness, cutting edge strength, wear resistance and dimensional stability. It is possible to exert a positive influence on all the parameters by vacuum heat treatment which is carefully selected to suit the HSS is determined by a choice of variable tempering temperatures, it is often impossible to optimise the mechanical properties, e.g. fracture toughness. A general recommendation for tools that require good impact strength, such as fine blanking tools, is that they should be hardened from temperatures as low as 1050°C[1]. By this treatment, resistance to tempering is diminished. For tools subjected to high pressures in service, a previous tempering at about 600°C[1] is recommended.

3. Experimental procedure

3.1 Material and treatment parameters

The test material selected was a conventional high-speed steel (HSS) of the AISI M2 type of the same melt. The chemical composition of the steel examined is listed in **Table 1**.

Table 1: Chemical composition of HSS examined (in wt.-%)

Material	C	Si	Mn	Cr	Mo	W	V	Co
AISI M2	0.87	0.29	0.30	3.77	4.90	6.24	1.81	0.53

Cylindrical round-notched tensile specimens with a diameter of 10 mm were machined from soft annealed bars with a Brinell hardness of 255. Specimens were fatigued to produce a sharp circumferential crack at the notch root, then austenitized in a vacuum furnace at temperatures of 1050°C, 1100°C, 1150°C and 1230°C respectively, quenched in a flow of gaseous nitrogen at a pressure of 5 bar abs. and double tempered one hour at temperatures 510°C, 540°C, 570°C and 600°C respectively.

3.2 Mechanical tests

The geometry of cylindrical round-notched precracked tensile specimens, prepared according Dieter's recommendation[4] is shown in **Fig. 2**.

Our previous investigations[5,6] confirmed that such small-scale specimens can be successfully used for the analysis of the relationship between the microstructural variations and the fracture toughness of the investigated steels. Accordingly to Grossmann's concept of hardenability, the formation of the uniform microstructure along the crack front is possible because of, the axial symmetry of the cylindrical specimens, in comparison with the conventional CT-specimens, where this condition is not fulfilled.

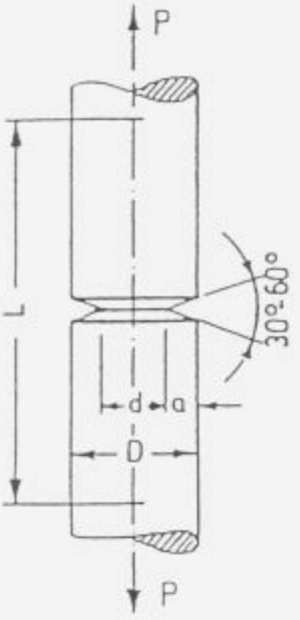


Figure 2: The geometry of a cylindrical round-notched and precracked tensile specimen

Slika 2: Nestandardni cilindrični natezni preizkušanec za merjenje lomne žilavosti z zarezo po obodu ter utrujenostno razpoko v korenu zareze

For a round-notched precracked specimen, the stress intensity factor is given by Dieter[4] as

$$KI = \frac{P}{D^{3/2}} (-1.27 + 1.72\ D/d) \qquad (1)$$

where d is the radius of the uncracked ligament after fatiguing, P is the applied fracture load, and D is the outer diameter of the cylindrical specimen. In the experiments, it is essential for the outer diameter of the specimen in order to obtain a state of plain strain at fracture.

In order to apply linear-elastic fracture mechanical concepts, the size of the plastic zone at the crack tip must be small compared with the nominal dimensions of the specimen. The size requirement for a valid KIC test is given by Shen Wei et. al.[7] as

$$D \geq 1.5\ (K_{IC}/\sigma_{ys}) \qquad (2)$$

where σ_{ys} is the yield stress of the investigated steel. This requirement (2) was fulfilled on all our measurements. The fracture surface of the cylindrical round-notched and precracked specimens was examined in SEM at low magnification. As is shown in Fig. 3, the fatigue crack propagation area was sharply separated from the circular central part of the fast fracture area, so that the diameter d of this area was easily measured.

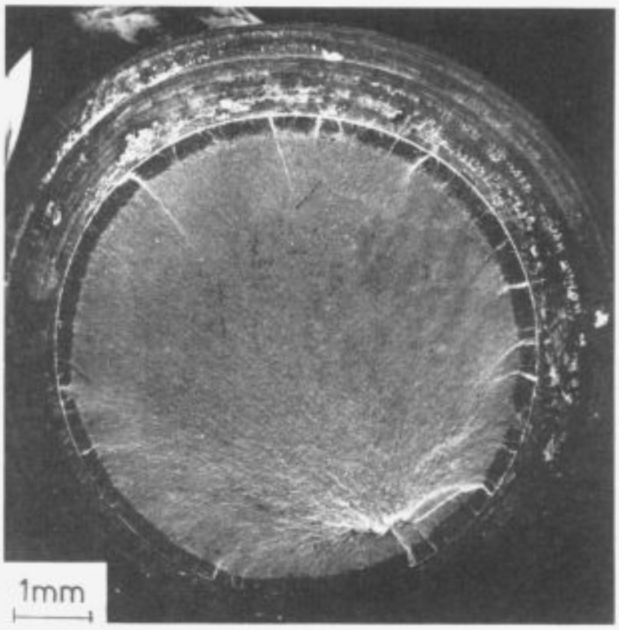


Figure 3: Fracture surface of cylindrical round-notched and precracked tensile specimen with the circumferential fatigue crack propagation area sharply separated from the circular central fast-fractured area

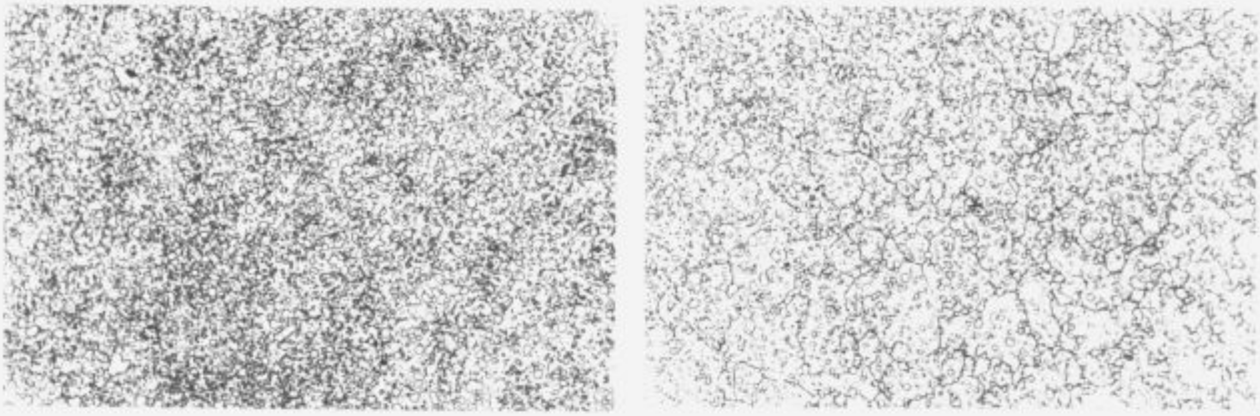
Slika 3: Prelomna površina cilindričnega nateznega preizkušanca z obodno zarezo, s kolobarjastim področjem propagacije utrujenostne razpoke, ki je ostro ločeno od osrednjega, naglo zlomljenega dela. Premer (d) naglo zlomljene prelomne površine lahko izmerimo z optičnim mikroskopom

4. Results and discussion

4.1 Microstructural characterisation

The microstructure develops in dependence on the hardening temperature, as well as the austenite grain size and the residual austenite content of the initial samples. Metallographic examination of specimens show that the austenite grain size of all specimens which were gas quenched from the austenitization temperature 1050 to 1230°C was 21 to 8 SG, **(Fig. 4)**.

The content of residual austenite in as queched condition was determined by X-ray diffraction. The absolute accuracy of the determination of the residual austenite contents was ± 1 vol%. The HSS AISI M2 steel is fine-grained, right up to high hardening temperatures, and exhibits a residual austenite contents between 21 and 30 vol%.

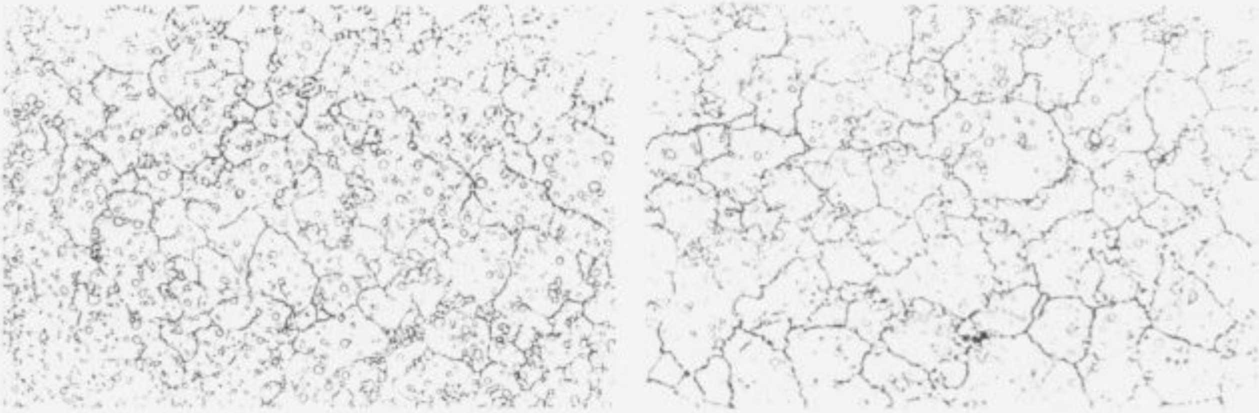


The microstructure after hardening at 1050°C, SG 21. Mag. 500x.

Mikrostruktura po kaljenju s temperature 1050°C, SG 21. pov. 500x.

The microstructure after hardening at 1100°C, SG 18. Mag. 500x.

Mikrostruktura po kaljenju s temperature 1100°C, SG 18. pov. 500x.



The microstructure after hardening at 1150°C, SG 13. Mag. 500x.

Mikrostruktura po kaljenju s temperature 1150°C, SG 13. pov. 500x.

The microstructure after hardening at 1230°C, SG 8. Mag. 500x.

Mikrostruktura po kaljenju s temperature 1230°C, SG 8. pov. 500x.

Figure 4: Microstructures with a different austenite grain size from vacuum hardened specimens from M2 steel

Slika 4: Mikrostruktura in velikost austenitnih zrn, vakuumsko kaljenih vzorcev z različnih temperatur austenitizacije

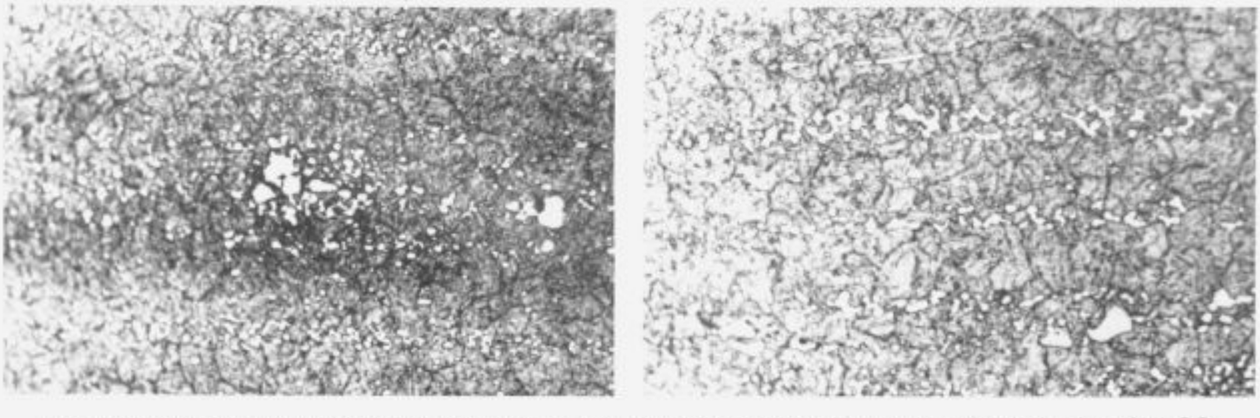


Figure 5: The microstructure shows carbides and tempered martensite with an austenite grain size of 13 SG (T_A:1150°C) and 8 SG (T_A:1230°C)

Slika 5: Mikrostruktura karbidov in popuščanega martenzita z velikostjo avstenitnih zrn SG 13 (T_A:1150°C) in SG 8 (T_A:1230°C)

The carbide particles in all the specimens were alike in size and position, which was due to their origin: all the specimens issued from the same metallurgical melt which was submitted to the same hot plastic transformation. The carbides looked like strips, and had a size of 1-20 μm, **(Fig. 5)**. The residual austenite contents are, with reference to tempering parameters, below 1 vol% in all samples. After metallographic etching, a stronger marking of the austenitic grain boundary could be noticed. L. Calliari

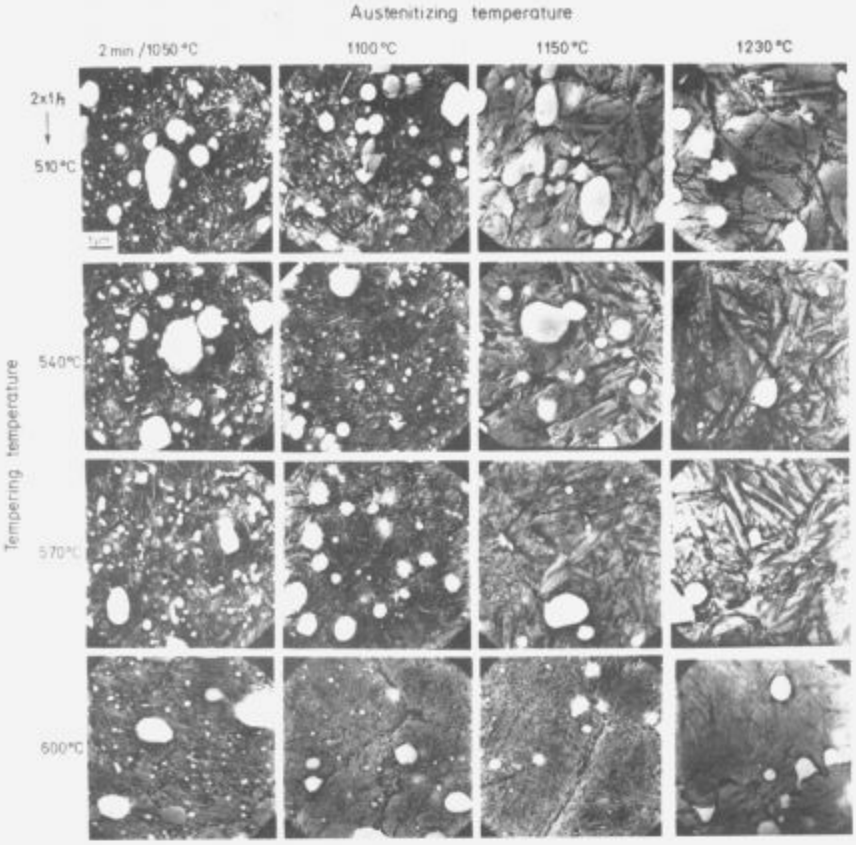


Figure 6: The microstructure of vacuum-hardened and tempered specimens examined by SEM

Slika 6: Mikrostruktura vakuumsko kaljenih in popuščenih vzorcev, posnetih na SEM pri 10 000 kratni povečavi

Table 2: Vacuum heat treatment parameters and mechanical properties of prepulsating round-notched tesion specimens

Vacuum heat treatment			Hardness HRc	Fracture toughness K_{IC} (MNm$^{-3/2}$)
Spec. No.	Hardening(°C) 2 min.	Tempering(°C) 2 x 1h		
01-02	1050	510	60.0	18.78
03-04	1050	540	60.5	18.26
05-06	1050	570	58.7	15.80
07-08	1050	600	52.8	16.43
09-10	1100	510	61.8	17.28
11-12	1100	540	62.2	15.69
13-14	1100	570	61.3	15.49
15-16	1100	600	55.0	16.99
17-18	1150	510	60.7	18.26
19-20	1150	540	63.3	13.14
21-22	1150	570	63.2	14.70
23-24	1150	600	57.8	15.63
25	1230	510	62.5	17.77
26	1230	540	65.0	10.55
27	1230	570	65.5	12.08
28	1230	600	63.0	12.95

et al.[8], compared vacuum and conventional heat-treated samples of AISI M2, and found that the results of over 100 tests did not point out noticeable differences among the samples treated with the two different procedures. Neither systematic data nor relationship with the treatment parameters are yet available on this subject.

The microstructure of the specimens examined by SEM at a higher magnification **(Fig. 6)** confirmed a carbide precipitation on the austenite grain boundaries for HSS M2 at different austenitizing and tempering temperatures. The quantity of fine carbide particles decreased with the increase of austenitizing temperatures. In addition, it was also noticed that at higher austenitizing temperatures, particularly at 1230°C (last column in **Fig. 6**), the larger carbide particles in contacts of austenite grains seemed to covering the boundaries of the neighboring grains because of variable surface tension on the matrix-carbides boundary. The microstructure of the specimens was of martensite type. The eventual presence of small quantities of retained austenite (1 to 5 vol%)[8] examined by optical microscopy, were too small to estimate without fail in such a heterogeneous microstructure. This phenomena can be attributed to the fact that the heating rate was lower in the vacuum furnace than in the salt bath. By heating the prepulsating round-notched tension specimens between 1050°C and 1230°C, diffusion processes in the vacuum furnace took longer than in the salt bath, which can possibly explain why, after metallographic etching, a more intensive marking of the austenitic grain boundary can also be noticed.

4.2 Mechanical tests

Experiments[9] were performed on 28 prepulsating round-notched tension specimens, **(Table 2)**, heat-treated in an IPSEN VTTC-324 R single chamber vacuum furnace with uniform high pressure gas quenching.

In the following, the assumption is made that the values K_{IC} are determined by the above-mentioned method. The obtained values of K_{IC} are very similar to those obtained by G. Hoyl[10], who determined the fracture toughness K_{IC} for HSS M2 steel, e.g. 18,3 $MNm^{-3/2}$ for sample austenitized 4 minutes at 1220°C and tempered 1 hour at 510°C, by conventional methods. Below a hardness level of about 50 HRc, fracture toughness is dependent only on the hardness of the sample[10]. At higher levels of hardness, the fracture toughness for M2 varies inversely with the austenitizing temperature, as shown in **Fig. 7**. G.Hoyl[10] discovered that above a hardness level of 60 HRc, fracture toughness is insensitive to most metallurgical factors.

The effects of tempering between 510 and 600°C on fracture toughness are shown for M2 in the same figure. As expected, there is a minimum of toughness values corresponding to the hardness peak. The net effect of tempering is attributed to a combination of stress relief and a reduction in ductility due to the secondary hardening effect.

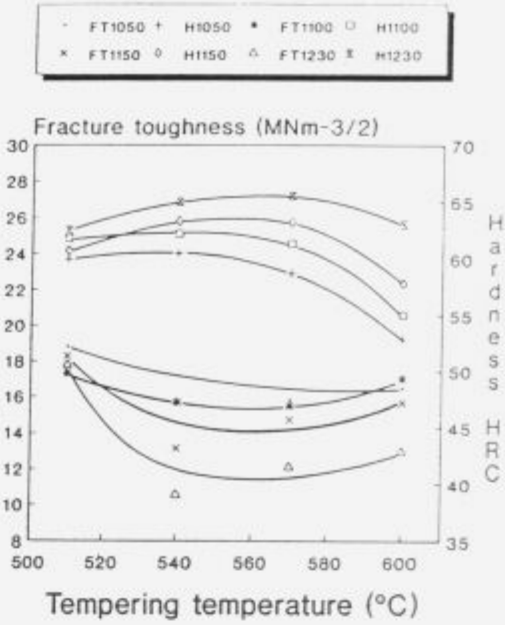


Figure 7: The effect of austenitizing and tempering temperature on fracture toughness and hardness of M2 steel (FT-fracture toughness; H-hardness)

Slika 7: Vpliv temperature austenitizacije in popuščanja na lomno žilavost KIC in trdoto, vakuumsko toplotno obdelanega hitroreznega jekla M2 (FT-lomna žilavost, H-trdota)

In examining the evolution of tempering[10], it was found that there was a peak value of fracture toughness for low tempering temperatures, (below 500°C). The obtained values are similar to those obtained in tempering at the conventional temperature, 25°C above the peak of the secondary hardening temperature. This is considered as advantageous, but as the effect is due to retained austenite that could transform later, the under-tempered tools could be susceptible to dimensional instability in service, which is unacceptable for fine blanking tools.

On the basis of the experimental results, it was possible to draw the diagram shown in **Fig. 8** where the technological parameters of the vacuum heat-treatment, mechanical properties and microstructure of the vacuum heat treated specimens are simultaneously combined.

From the diagram in **Fig. 8**, it is also evident that the fracture toughness for the tempering temperatures 540°C, 570°C and 600°C, respectively, increases with the decrease of hardening temperature in agreement with observations in reference 10. On the other hand, for the tempering temperature of 510°C, it was found that the fracture toughness values were very close, though slightly higher than for 600°C, irrespective of the hardening temperatures. On the basis of the curves in **Fig. 8**, it can be reliably assumed that the HSS M2 hardened from low austenitizing temperatures and tempered at 510°C can achieve the optimal combination of hardness and fracture toughness.

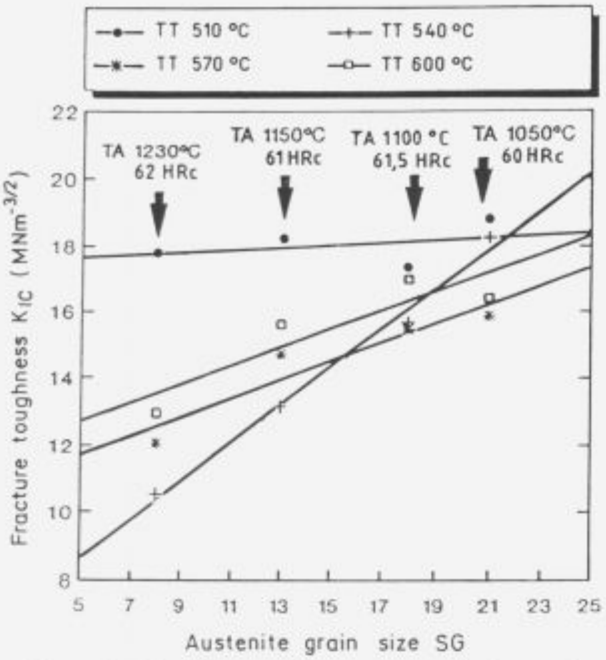


Figure 8: The influence of austenite grain size on the fracture toughness of HSS AISI M2, (TT-tempering temperature, TA-hardening temperature, HRc-hardness at 510° C)

Slika 8: Vpliv velikosti austenitnega zrna na lomno žilavost hitroreznega AISI M2, (TT-temperatura popuščanja, TA-temperatura kaljenja, HRc-trdota po pop. na temperaturi 510° C)

The relationship between fracture toughness and austenite grain size, f.i. SG grade 8, shows us that at the tempering temperatures between 510 and 600° C, the obtained values K_{IC} are from 17,77 to 10,55 $MNm^{-3/2}$ and the difference is quite important in practice. Different fracture toughness at equal austenite grain size or the nearly constant fracture toughness of HSS M2 hardened from different austenitizing temperatures, f.i. from 1050 to 1230° C, and double tempered at 510° C, is in accordance with the hypothesis that the austenite grain size is not the dominant parameter effecting the fracture toughness of HSS M2.

The result of the present investigation is useful for the optimisation of vacuum heat treatment for different HSS tools submitted to tensile impact stress during use where an optimal combination of hardness and fracture toughness are decisive.

4.3 Tool life tests

Long production runs have underlined the importance of an improved fine blanking tool life, **(Fig. 9)**.

On the basis of the experimental results shown in **Fig. 8**, it was found that the optimum vacuum heat treatment of fine blanking HSS M2 tools needs at least two preheating stages (650 and 850° C respectively), a variable hardening temperatures (usually 1050 to 1150° C) and double tempering at the same temperature (510° C/1hour).

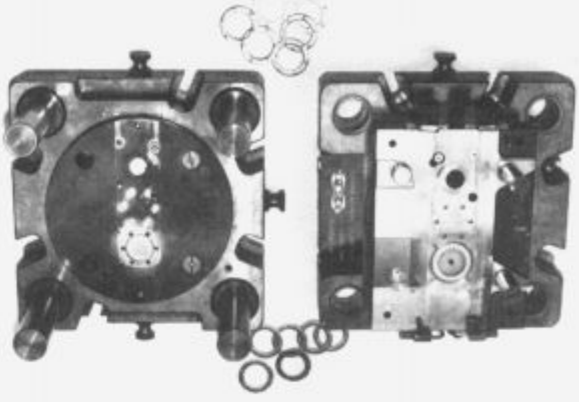


Figure 9: Fine blanking tool for a ratchet wheel

Slika 9: Orodje za precizno štancanje zobnika varnostnega pasu

The life of a fine blanking tool varies considerably depending on the size and design of the blank, the type of blanking steel, and care and maintenance. To establish tool life, we selected three tools for a fine blanking ratchet wheel. The punches and dies were from HSS AISI M2. Blanks with a material gauge of 4 mm were from AISI C 1045 blanking steel in a spheroidized-annealed condition. The punches and dies were stress-relieved at 650° C 4 hours and vacuum heat-treated in a single chamber vacuum furnace with uniform high pressure gas quenching. Depending on the alloying and the condition of austenitization (1100° C/2min), the final hardness of 61.5 HRc and the final fracture toughness of 17.28 $MNm^{-3/2}$ was reached after double tempering at 510° C for 1 hour **(Fig. 8)**. The vacuum heat-treated punches and dies were tested on a 250t triple-action hydraulic press and compared with the fine blanking tools for fine blanking ratchet wheels conventionally heat-treated in a salt bath as follows: stress relieved at 650° C/4hour, preheated at 450° C, 650° C and 850° C respectively, austenitized at 1100° C/2min and control-quenched to 550° C in 5 min, held isothermally at 550° C for 10 min and cooled to 80° C with air, followed by double tempering at 600° C/1 hour. The final hardness of the tools achieved after double tempering at 600° C/1 hour, was 58 to 59 HRc, depending on the alloying.

The basic trial parameters (such as the cutting force, strikes per time unit, temperature, greasing etc.) were constant during the experiments, and did not affect the final results. The differences observed in fine blanking tools could only originate in the punches and dies themselves. 15.000 ratchet wheels were made with each tool and edges examined in a binocular microscope to estimate the damage. Minor defects were observed on the vacuum heat-treated punches and dies and those conventionally heat-treated in a salt bath.

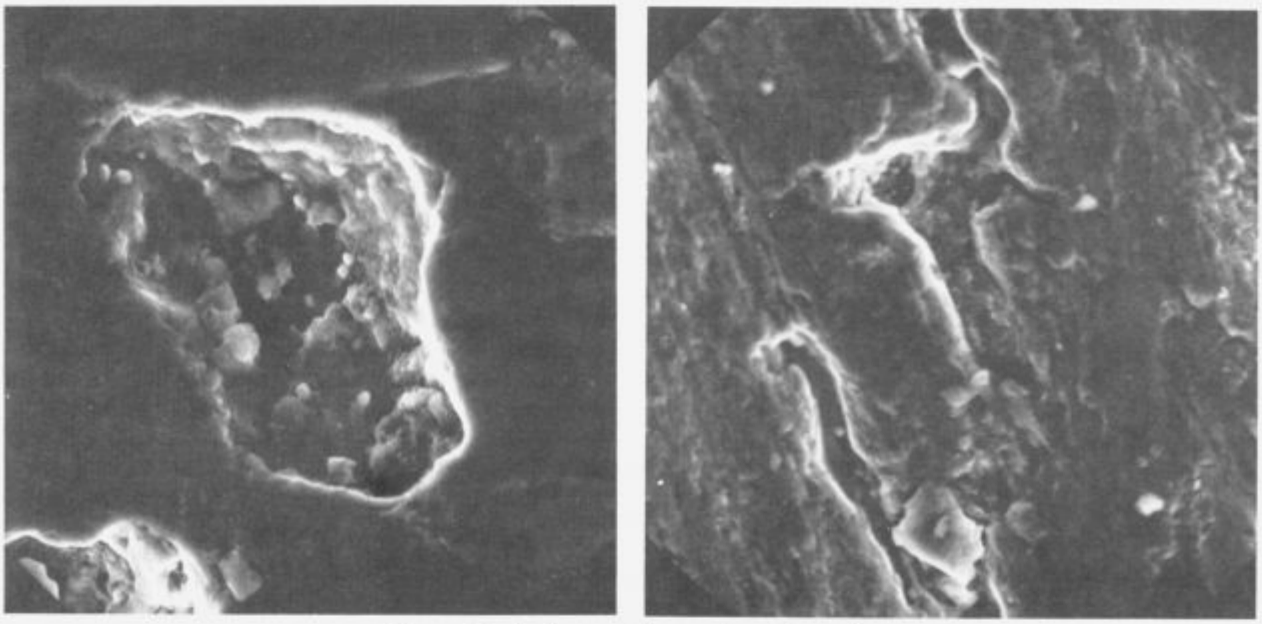


Figure 10: Defects on the punch cutting edge

Slika 10: Poškodbe na rezilnem robu pestiča

The wear of the punches and dies increases with the operation time. SEM observations show that the starting wear of the cutting edges of the punches and dies could not be easily determined. The material showed not only surface fatigue, but also adhesion and abrasion, **(Fig. 10)**.

The experiments showed that higher working hardness (61.5 HRc) and improved fracture toughness of vacuum heat-treated punches and dies - particularly those double-tempered at 510°C - had significant effect on the defects on the cutting edges. Compared to conventionally heat treated tools tempered at 600°C was the vacuum heat-treated tool life by 15 to 20%, greater. During the tool tests, no effects were found that could be related to the in service dimensional instability due to the later-transformed retained austenite. Namely, X-ray structural analyses showed that the content of retained austenite did not exceed 1 vol% in all the specimens.

5. Conclusions

The exact significance of fracture toughness as it affects HSS properties and service behavior is not thoroughly understood, and there are differences in behavior between grades and process routes. However, the modified method for the establishment of fracture toughness improved by IMT, appeared to be a successful method for establishing the fracture toughness of HSS.

The measurements of wear in the cutting edges of punches and dies show that double tempering at 510°C/1h after vacuum heat treatment prolongs the life of fine blanking tools for ratchet wheels by 15 to 20%, compared to conventionally heat-treated tools which were hardened at the same austenitizing temperature and tempered twice at 600°C. It seams that it is not the type of process which substantially affects the tool life, but first of all, the proper choice of hardening and tempering temperatures.

The wear resistance of punches and dies cannot only be described as a material property, but as a property of a complex tribological system. Yet, it is proven that the wear resistance depends, above all, on the microstructure of the tool material and on its physical and chemical properties.

The presented results, obtained by the evaluation of daily confirmed data, justify the use of modern vacuum heat-treatment technology and the use of the newest high-performance HSS steels to achieve great improvements in tool lives and overall economy.

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