

Influence of the heat treatment on the toughness of some hot-work tool steel grades

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The influence of heat treatment on the toughness of a number of hot-work tool steel grades used for e.g. die-casting has been researched. The researched grades were X40CrMoV5-1, X37CrMoV5-1 and Dievar: an improved hot-work tool steel grade developed by Uddeholm. The impact toughness was researched by conventional Charpy V-notch testing and instrumented Charpy V-notch testing at various temperatures.

The fracture toughness was studied by K_{Ic} testing at room temperature and J_{Ic} testing at elevated temperatures. The influence of the hardness and the cooling rate during quenching were examined. Additionally, the toughness after austempering was measured and compared with the toughness after quenching and tempering to equivalent hardness. The influence of preheating of the die on the toughness was studied by impact and fracture toughness measurements at various temperatures.

The energy absorption in impact testing decreased throughout the whole temperature range with increasing hardness and decreasing quenching rate. The fracture toughness decreased also with increasing hardness and decreasing quenching rate. Austempering followed by tempering gave a lower toughness than conventional hardening and tempering to equivalent hardness. Preheating of the die increases the toughness considerably.

Key words: Hot-work tool steel, K_{Ic} fracture toughness, J_{Ic} fracture toughness, instrumented impact testing, Charpy V-notch impact testing, elevated temperature, transition curve, hardness, quenching rate

INTRODUCTION

In order to minimise the risk of gross cracking the toughness of dies and moulds should be as high as possible. In order to maximise the toughness it is necessary to

- Choose a steel grade with high toughness
- Heat treat to a low hardness
- Perform the heat treatment in an optimum way
- Preheat the die properly before the production starts.

There are of course differences in toughness between different grades. Some results from the testing of three hot-work tool steel grades are discussed in this presentation but one should not draw general conclusions about differences in toughness between the three grades from these results. The second possibility is generally not applicable in practice. The hardness is determined by the requirements on resistance against plastic deformation, mechanical fatigue and thermal fatigue. Although the influence of the hardness on toughness is discussed this presentation deals mainly with the influence of the heat treatment on toughness. The influence of the cooling rate during quenching and differences between austempering and conventional hardening are discussed. Finally the importance of preheating is addressed.

EXPERIMENTATION

The heat treatment trials were mainly made in a Schmetz vacuum furnace with a maximum nitrogen overpressure of 5 bars. The temperature of the specimens were determined by using a type N thermocouple mounted in a dummy specimen.

Toughness was measured by fracture toughness testing, conventional Charpy V-notch impact testing and instrumented impact testing.

The fracture toughness testing was performed in an MTS 700 kN servohydraulic universal testing machine. The ASTM standard for K_{Ic} fracture toughness testing E399 [1] and J_{Ic} fracture toughness testing E813-89 [2] were followed. Compact tension (CT) specimens were used. Specimens with $W=34$ mm and $B=17$ mm were generally used. At lower hardness larger specimens, $W=70$ and $B=35$ mm, were used in K_{Ic} fracture toughness testing.

Charpy V-notch impact testing was performed in a 150 J impact pendulum manufactured by Roell-Amsler. In a conventional test the energy absorption is calculated from the weight and the angles of release and rise of the pendulum. The testing was performed according to the European standards for impact testing, EN 10 045-1 [3].

In instrumented impact testing the tup that breaks the specimen is equipped with strain gauges which allows the force acting on the specimen during the testing to be calculated. At instrumented impact testing, force versus time curves can consequently be obtained. The displacement, s , is calculated from the time, t , the force, F , the mass of the pendulum, m , and the initial pendulum velocity, v_0 , by a double numeric integration:

$$v(t) = v_0 - \frac{1}{m} \int_{t_0}^t F(t) dt \quad (1)$$

$$s(t) = \int_{t_1}^t v(t) dt \quad (2)$$

where t_0 is time at the beginning of the deformation. Instead of force versus time curves force versus displacement curves can thus be obtained.

The energy absorbed is calculated from the area under the

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Steel grade	Cross section of bar			
X40CrMoV5-1	407x127 mm	762x305 mm	610x153 mm	508x127 mm
X37CrMoV5-1	500x100 mm			
Uddeholm Dievar	610x203 mm	700x300 mm	915x407 mm	

Table 1 – Test material. Dievar is the brand name for a hot-work tool steel developed by Uddeholm.
Tab. 1 – Materiali e dimensioni delle barre in prova (Dievar è il nome commerciale di un acciaio da utensile per lavorazione a caldo sviluppato da Uddeholm).

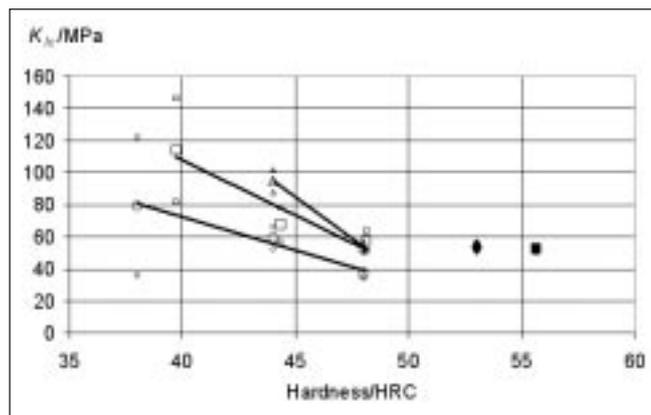


Fig. 1 – Plain strain fracture toughness versus hardness. ● and ○ indicate X40CrMoV5-1 407x127 mm, ■ and □ indicate X37CrMoV5-1 500x100 mm and △ indicates Dievar 610x203 mm. Empty symbols indicate high-temperature tempering whereas solid symbols indicate low temperature (200°C) tempering. Austenitizing of X40CrMoV5-1 and Dievar: 1025°C 30 min. Austenitizing of X37CrMoV5-1: 1010°C 30 min. Cooling time between 800°C and 500°C: 170-320 s. The corresponding mean cooling rates in the temperature interval are 105-56°C/min. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 1 – Tenacità alla frattura in rapporto alla durezza. I simboli ● e ○ indicano l'acciaio X40CrMoV5-1 da 407x127 mm, ■ e □ l'acciaio X37CrMoV5-1 da 500x100 mm e △ l'acciaio Dievar da 610x203 mm. I simboli vuoti sono relativi al rinvenimento ad alta temperatura mentre i simboli pieni indicano quello a bassa temperatura (200°C). Austenitizzazione degli acciai X40CrMoV5-1 e Dievar: 30' a 1025°C. Austenitizzazione dell'acciaio X37CrMoV5-1: 30' a 1010°C. Tempo di raffreddamento da 800°C a 500°C: 170 e 320 s; in questo intervallo di temperature le corrispondenti velocità medie di raffreddamento sono 105 e 56°C/60 s. I simboli più grandi indicano i valori medi mentre quelli piccoli ne rappresentano gli intervalli di confidenza del 90%.

curve. According to EN ISO 14556:2000 [4] the force-time or force-displacement curves are classified into six different types. Several characteristic values of force and displacement can be determined. In this presentation the curve types are not discussed at all and only the maximum force, the general yield force and the maximum displacement are shown.

TEST MATERIAL

The test materials are shown in table 1. Unless nothing else is indicated the specimens were cut from the centre of the bar. They were cut in such a way that the normal to the crack plane was in the short transverse direction of the bar and the direction of growth of the crack during testing was in the long transverse direction. This type of specimens are designated S-T. The number of specimens varied from test to test.

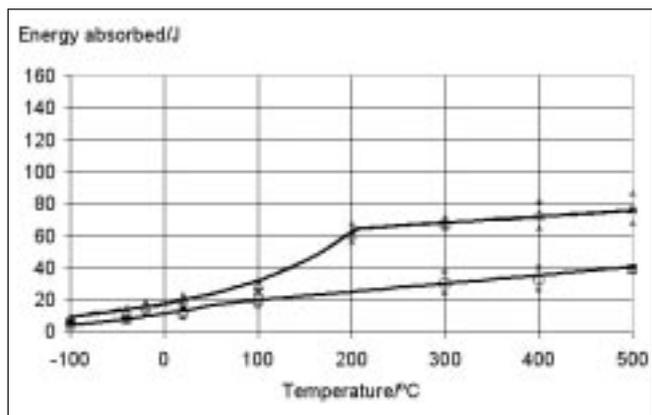


Fig. 2 – Charpy-V notch impact toughness versus temperature of X40CrMoV 407x127 mm. □ indicates 48 HRC and △ indicates 45 HRC. Austenitizing: 1025°C 30 min. Cooling time between 800°C and 500°C: 30 s. Tempering 2+2 h at 590°C and 610°C, respectively. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 2 – Prova di resilienza Charpy - V a diverse temperature per l'acciaio X40CrMoV da 407x127 mm. □ indica 48 HRC e △ indica 45 HRC. Austenitizzazione: 30' a 1025°C; tempo di raffreddamento da 800°C a 500°C: 30 s; rinvenimento 2+2 h a 590°C e 610°C, rispettivamente. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

TEST RESULTS AND DISCUSSION

Influence of the hardness on the fracture toughness

Figure 1 shows the influence of the hardness on the fracture toughness of X40CrMoV5-1, X37CrMoV5-1 and Dievar. The reason for the considerable scatter at the lowest hardness is that only two valid values were obtained in the tests. At testing of the specimens at higher hardness three or four valid K_{Ic} values were obtained. ASTM E399 [1] recommends at least three values.

At high hardness low-temperature tempering seems to give higher toughness than high-temperature tempering. This is what is usually observed. One factor that contributes to the higher toughness after low temperature tempering is that the yield strength is lower than after high-temperature tempering to an equivalent hardness.

The toughness values for the low hardness are slightly underestimated due to the fact that the cooling rate of the specimens was slightly lower than for the harder specimens. The reason for this is that larger specimens were used in order to fulfil the size criteria according to ASTM E399 [1].

Influence of the hardness on the impact toughness

Figure 2-4 show transition curves of X40CrMoV5-1, X37CrMoV5-1 and Dievar at various hardness. The hardness has a large influence on the energy absorption, especially at high temperatures. No clear lower or upper energy shelf is present for Dievar. The energy absorption, especially at higher temperatures, is considerably higher than for the other two grades.

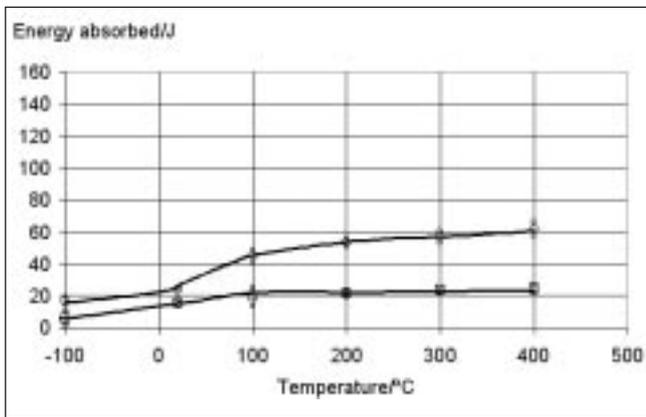


Fig. 3 – Charpy–V notch impact toughness versus temperature of X37CrMoV 500x100 mm. □ indicates 48 HRC and ○ indicates 39 HRC. Austenitizing 1010°C 30 min. Cooling time between 800°C and 500°C: 30 s. Tempering 2+2 h at 200°C, 585°C and 625°C, respectively. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 3 – Prova di resilienza Charpy - V a diverse temperature per l'acciaio X37CrMoV da 500x100 mm.

□ indica 48 HRC e ○ indica 39 HRC. Austenitizzazione: 30' a 1010°C; tempo di raffreddamento da 800°C a 500°C: 30 s rinvenimento 2+2 h a 200°C e 585°C, rispettivamente. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

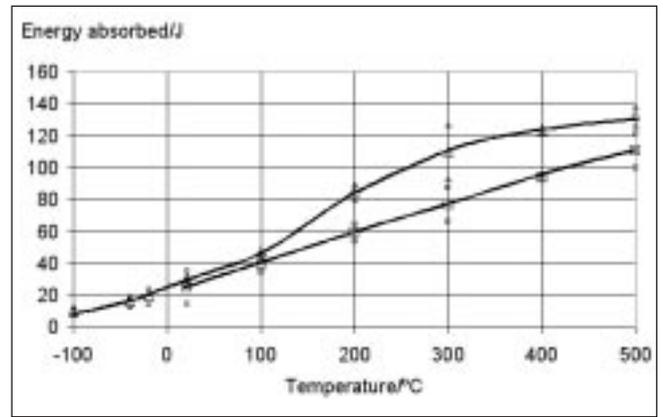


Fig. 4 – Charpy–V notch impact toughness versus temperature of Dievar 610x203 mm. □ indicates 47 HRC and Δ indicates 45 HRC. Austenitizing 1030°C 30 min. Cooling time between 800°C and 500°C: 30 s. Tempering 2+2 h at 605°C and 610°C, respectively. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 4 – Prova di resilienza Charpy - V a diverse temperature per l'acciaio Dievar da 610x203 mm.

□ indica 48 HRC e Δ indica 45 HRC. Austenitizzazione: 30' a 1030°C; tempo di raffreddamento da 800°C a 500°C: 30 s; rinvenimento 2+2 h a 605°C e 610°C, rispettivamente. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

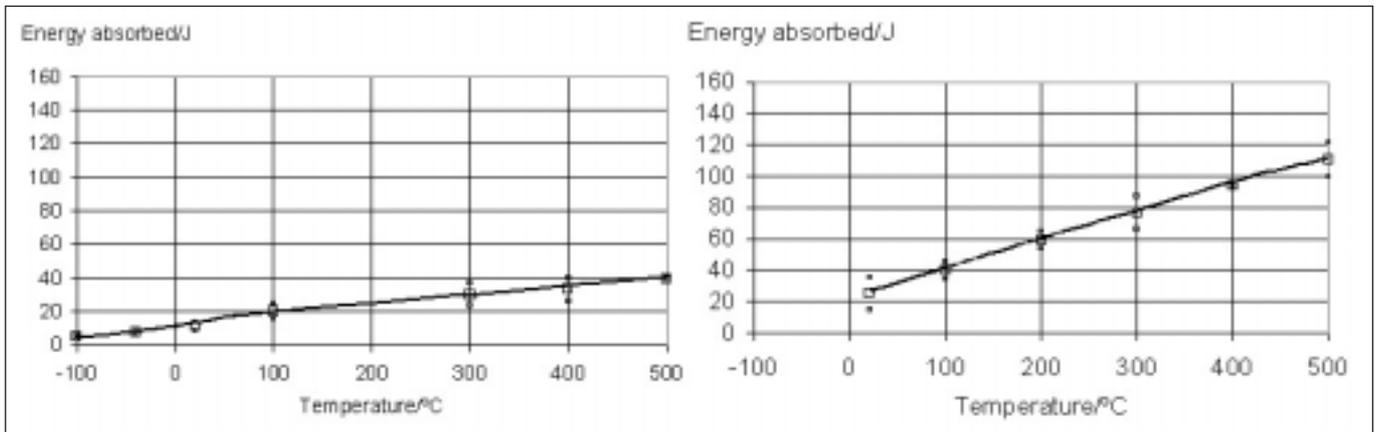


Fig. 5 – Charpy –V notch impact toughness versus temperature of X40CrMoV5-1 427x127 mm at 48 HRC (left) and Dievar 610x203 mm at 47 HRC (right). Heat treatment according to figure 4 and 5. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 5 - Prova di resilienza Charpy - V a diverse temperature per l'acciaio X40CrMoV5-1 da 427x127 mm.

Trattamento termico secondo le figg. 4 e 5. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

The considerable difference in energy absorption between X40CrMoV5-1 and Dievar at 37-38 HRC is obvious if figure 2 and 4 are compared but for the sake of clarity it shown in figure 5. The testing of these grades was performed as instrumented tests. It is therefore possible to determine why the energy absorption differs so much.

The general yield force versus test temperature for Dievar is shown in figure 6. It could be expected that X40CrMoV5-1 should have a slightly higher yield force than Dievar due to it being slightly harder. The hardness was actually 1,2 HRC higher than for Dievar as the hardness of the two grades were 48,2 HRC and 47,0 HRC, respectively. However general yielding did not begin in X40CrMoV5-1 until the temperature reached 400°C. The general yield force at this temperature was 30,7 kN. The specimens broke before general yielding at all test temperatures below 400°C.

Figure 7 shows the maximum force. At temperatures below

300°C it is slightly higher for Dievar than for X40CrMoV5-1. At and above 300°C the maximum force of the two test materials are equivalent.

Figure 8 shows the displacement. The displacement is, as a matter of fact, the position of the tup when the force passes zero, that is when the specimen is completely broken. Therefore the displacement corresponds roughly with how much the specimen bends before it breaks. Figure 8 shows that there is a huge difference between X40CrMoV5-1 and Dievar. For the former steel grade the displacement increases slowly while for the latter grade it increases quickly with increasing temperature.

As the energy absorption is calculated from the force-displacement curve it becomes clear that the higher energy absorption of Dievar is a consequence of the fact that the displacement for this grade is much larger than for X40CrMoV5-1.

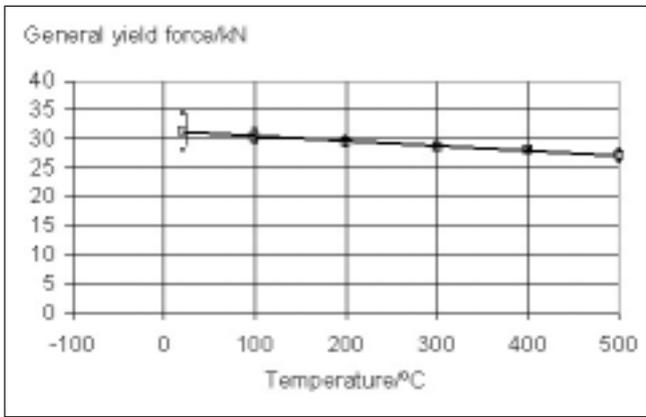


Fig. 6 – General yield force versus temperature for Dievar 610x203 mm at 47 HRC. Heat treatment according to figure 4. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 6 – Forza di snervamento globale in funzione della temperatura per l'acciaio Dievar da 610x203 mm a 47 HRC. Trattamento termico secondo la Fig. 4. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

Influence of the cooling rate during quenching on the fracture toughness

The influence of the cooling rate expressed as the cooling time between 800 °C and 500 °C on the fracture toughness has been examined for Dievar and the result is shown in figure 9. From figure 9 it seems that the fracture toughness decreases more or less linearly with increasing cooling time up to about 1000 s. Then it remains at a constant level up to very long cooling times.

Influence of the cooling rate during quenching on the impact toughness

Figure 10 shows the impact toughness of Dievar heat treated in the same way as the specimens in figure 9. The decrease in energy absorption with increasing cooling time is more pronounced than the decrease of fracture toughness, especially with short cooling times.

Due to the large scattering of results in the tests, which can be seen in the large confidence interval widths, it becomes difficult to say if the decrease in toughness is faster in certain cooling time ranges than in others. In order to collect such information more cooling times must be included and, in order to reduce the confidence interval width, more specimens must be tested at each cooling time. Therefore an addi-

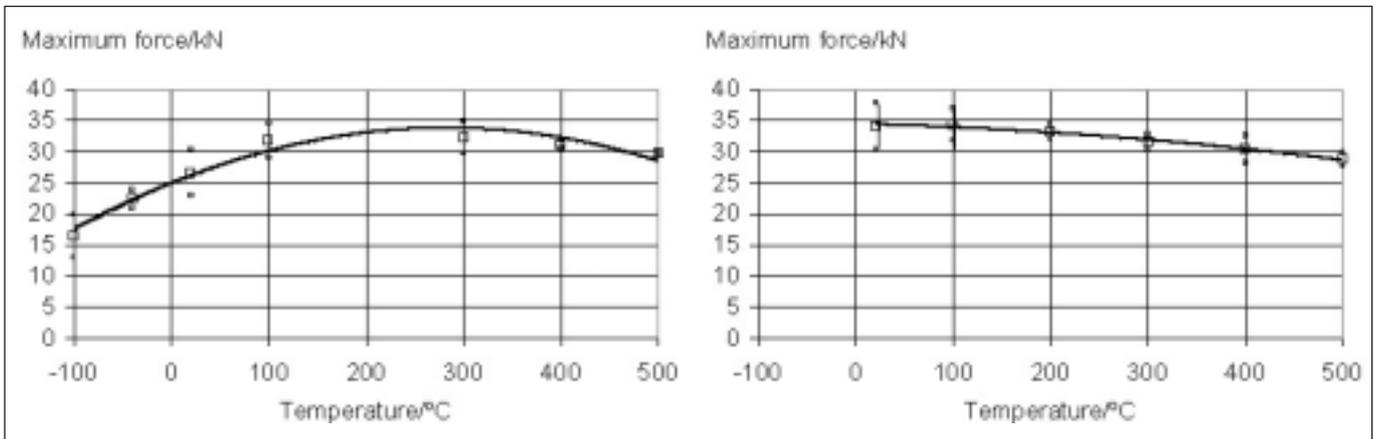


Fig. 7 – Maximum force versus temperature of X40CrMoV5-1 407x127 mm at 48 HRC (left) and Dievar 610x203 mm at 47 HRC (right). Heat treatment according to figure 4 and 5. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 7 – Carico massimo in funzione della temperatura per l'acciaio X40CrMoV5-1 da 427x127 mm a 48 HRC. Trattamento termico secondo le figg. 4 e 5. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

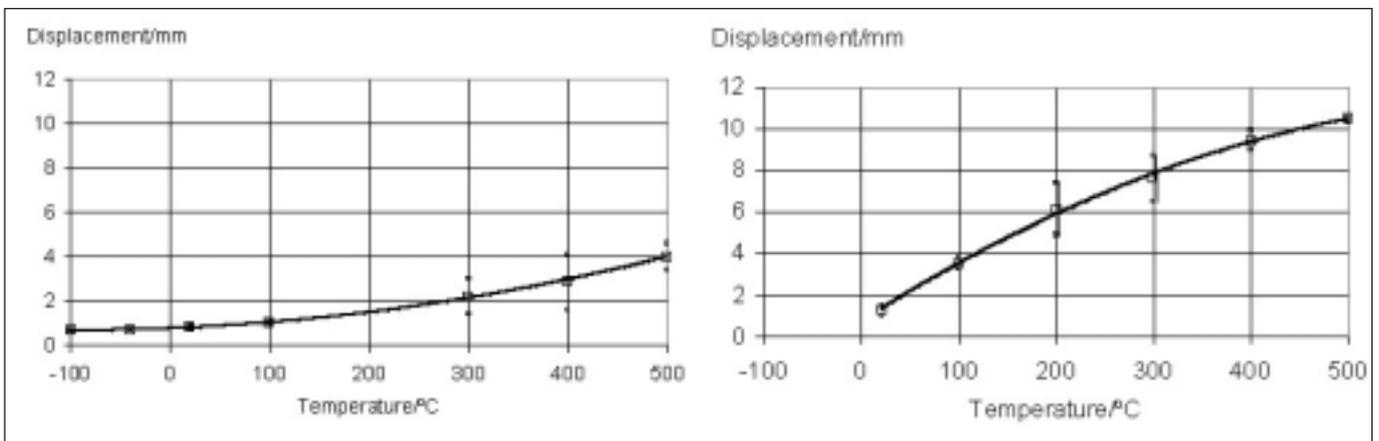


Fig. 8 – Displacement versus temperature. X40CrMoV5-1 427x127 mm at 48 HRC (left) and Dievar 610x203 mm at 47 HRC (right). Austenitizing 30 min at 1010°C and 1030°C, respectively. Cooling time between 800°C and 500°C: 30 s. Tempering 2+2 h at 585°C and 605°C, respectively. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 8 - Spostamento in funzione della temperatura. Acciaio X40CrMoV5-1 di 427x127 mm a 48 HRC (sinistra) e acciaio Dievar 610x203 mm a 47 HRC (destra). Austenitizzazione: 30' a 1010°C e 1030°C, rispettivamente. Tempo di raffreddamento da 800°C a 500°C: 30 s. Rinvenimento 2+2 h a 585°C e 605°C, rispettivamente. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

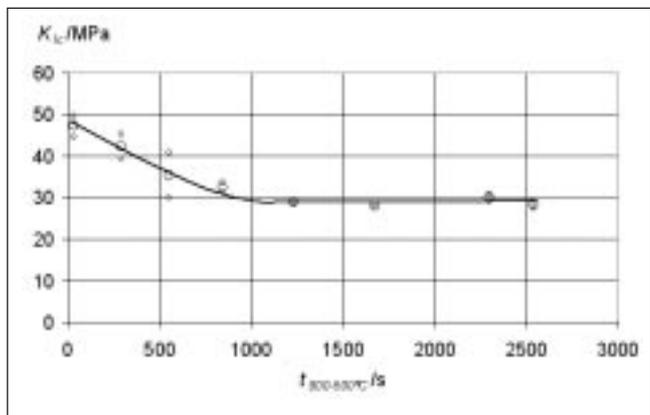


Fig. 9 – Fracture toughness of Dievar 700x300 mm. Austenitizing: 1025°C 30 min, quenching at various velocities. Tempering: 2+2 h at 590°C. Hardness 49-51 HRC. Specimens from surface of the bar. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 9 – Tenacità alla frattura dell'acciaio Dievar 700x300 mm. Austenitizzazione: 30' a 1025°C. Raffreddamento a varie velocità. Rinvenimento 2+2 h a 590°C. Durezza 49-51 HRC. Provini dalla superficie della barra. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

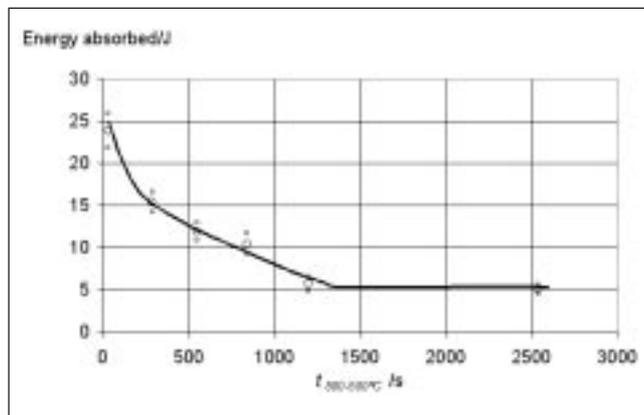


Fig. 10 – Impact toughness of Dievar 700x300 mm. Austenitizing: 1025°C 30 min, quenching at various velocities. Tempering: 2+2 h at 590°C. Hardness 49-51 HRC. Specimens from surface of the bar. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 10 – Tenacità all'impatto dell'acciaio Dievar 700x300 mm. Austenitizzazione: 30' a 1025°C. Raffreddamento a varie velocità. Rinvenimento 2+2 h a 590°C. Durezza 49-51 HRC. Provini dalla superficie della barra. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

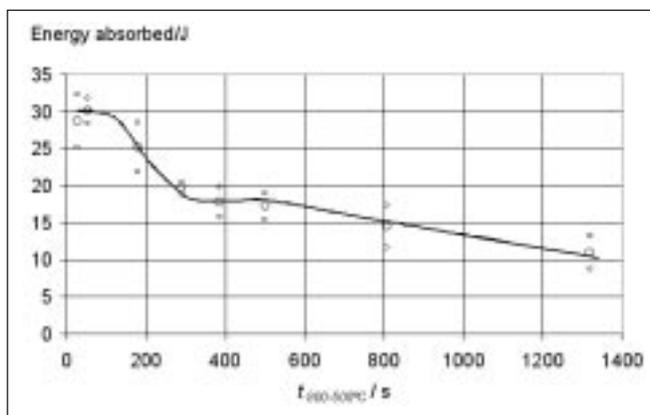


Fig. 11 – Impact toughness of Dievar 305x127 mm. 1020°C 30 min, quenching at various rates. Tempering 2 h at 600°C and 2 h at 605 HRC. Hardness 46-47 HRC. Large symbols indicate mean values and small symbols 99% confidence intervals for the mean.

Fig. 11 – Tenacità all'impatto dell'acciaio Dievar 305x127 mm. Austenitizzazione: 30' a 1020°C. Raffreddamento a varie velocità. Rinvenimento 2 h a 600°C e 2 h a 605 °C. Durezza 46-47 HRC. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

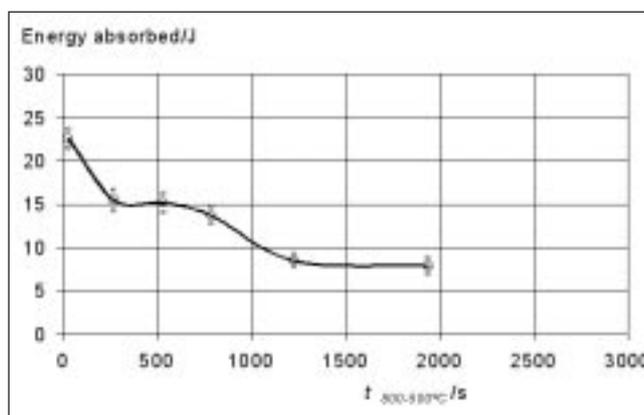


Fig. 12 - Impact toughness of X40CrMoV5-1 762x305 mm. 1025°C 30 min, quenching at various rates. Tempering 2+2 h at 610°C. Hardness 45-46 HRC. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 12 – Tenacità all'impatto dell'acciaio X40CrMoV5-1 da 762x305 mm. Austenitizzazione: 30' a 1025°C. Raffreddamento a varie velocità. Rinvenimento 2+2 h a 610°C. Durezza 45-46 HRC. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

tional test was done with 12 or 24 specimens at each cooling time. In this case 99% confidence intervals were calculated. As no further decrease in toughness at cooling times above 1200 s was observed in the previous test only one cooling time longer than that was included. The result is shown in figure 11.

At very short cooling times there is no significant influence of the cooling rate on the impact toughness. Between 50 s and 300 s the energy absorption decreases from 30 J to 18 J. In the time range between 400 s and 500 s or slightly more no further decreases occurs. Above approximately 500 s the toughness decreases with increasing cooling rate again but at a lower rate.

A diagram similar to figure 10 was made for X40CrMoV5-1. The result is shown in figure 12. In this case it is clear that the rate of decrease in impact toughness is different in different cooling time ranges.

North American Die Casting Association (NADCA) recommends a minimum (mean) quench rate 15 mm below the surface of 28°C/min for X40CrMoV5-1 in the temperature range 1030-540°C [5]. Internal research has shown that the cooling rate between 1030°C and 540°C roughly corresponds to the same rate in the interval 800°C and 500°C. This means that 28°C/min between 1030°C and 540°C corresponds to 640 s between 800°C and 500°C. NADCA's recommendation seems to be reasonable. The impact toughness is certainly reduced in comparison with the example obtained at very fast quenching, however this is an inevitable result. A cooling time of some tens of seconds is only obtained if specimens are heat treated. It is not possible to reach in real dies or moulds. The reduction in impact toughness seems to be about 40% if the recommendation of the NADCA is followed. If the cooling time between 800°C and 500°C is allowed to increase to 1200 s (corresponds to a

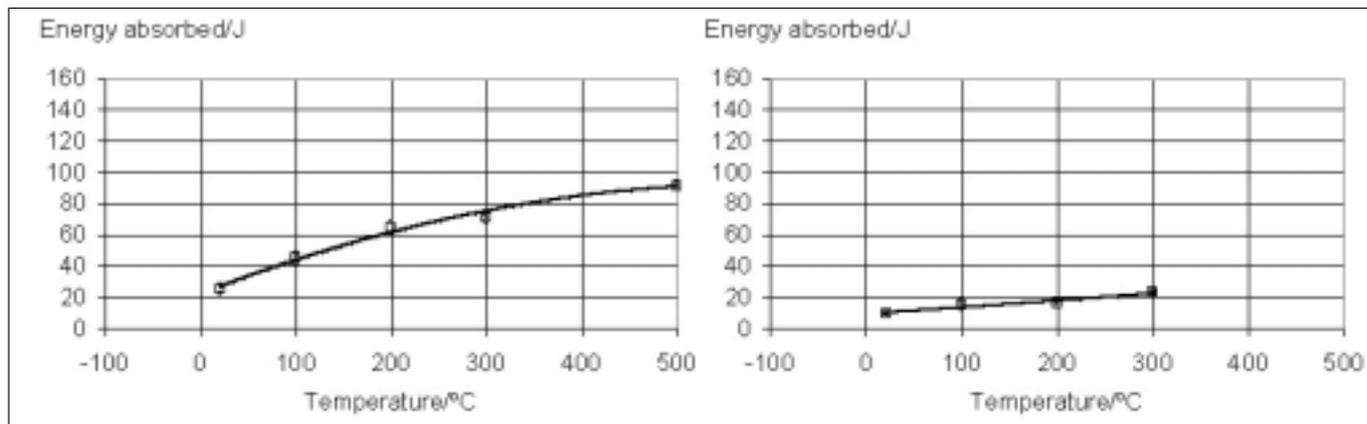


Fig. 13 – Energy absorption at Charpy V-notch impact testing of Dievar 700x300 mm. Austenitizing 30 min at 1030°C, cooling time in the interval 800-500°C 30 s and 1200 s, respectively. Tempering at 615°C to 44 HRC. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 13 – Assorbimento di energia nella prova Charpy - V dell'acciaio Dievar da 700x300 mm. Austenitizzazione: 30' a 1030°C; raffreddamento nell'intervallo 800-500 °C, 30s e 1200 s rispettivamente. Rinvenimento a 615°C per 44 HRC. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

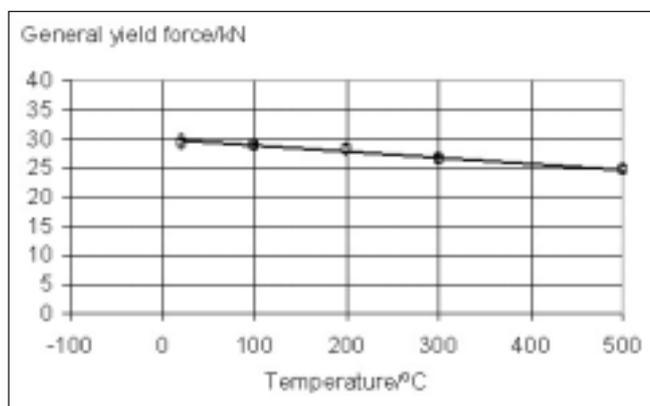


Fig. 14 – General yield force at impact testing of Dievar 700x300 mm. Austenitizing 30 min at 1030°C, cooling time in the interval 800-500°C 30 s. Tempering at 615°C to 44 HRC. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 14 – Forza di snervamento globale nella prova di impatto dell'acciaio Dievar da 700x300 mm. Austenitizzazione: 30' a 1030 °C; raffreddamento nell'intervallo 800-500 °C, 30s. Rinvenimento a 615°C per 44 HRC. I simboli più grandi indicano i valori medi mentre i piccoli rappresentano gli intervalli di confidenza del 90%.

mean quenching rate between 1030°C and 540°C of about 20°C/min) the reduction in impact toughness is about 70%.

A comparison between figures 9 and 10 shows that the reduction in fracture toughness due to slow quenching seems to be smaller than the reduction in impact toughness.

It is interesting to see how the transition curves change if the cooling is changed from very fast to very slow. Figure 13 shows this. As the tests were carried out with an instrumented tup both energy absorption, force and displacement values were recorded and these are displayed in figure 14-16. The diagrams show that an increase of the cooling time in the temperature range 800°C to 500°C from 30 s to 1200 s reduces the energy absorption at impact testing dramatically. The reason for the reduction in energy absorption is that the displacement is reduced. This is a consequence of the fact that the specimens which are quenched slowly break before general yielding occurs.

Influence of austempering on the toughness

The preceding sections show that the cooling rate during quenching has a strong influence on both fracture toughness and impact toughness. In order to obtain high toughness the quenching rate must be high. However if the quenching rate is too high it can result in heavy distortion and the obvious risk of quenching cracking. Could austempering be a solution?

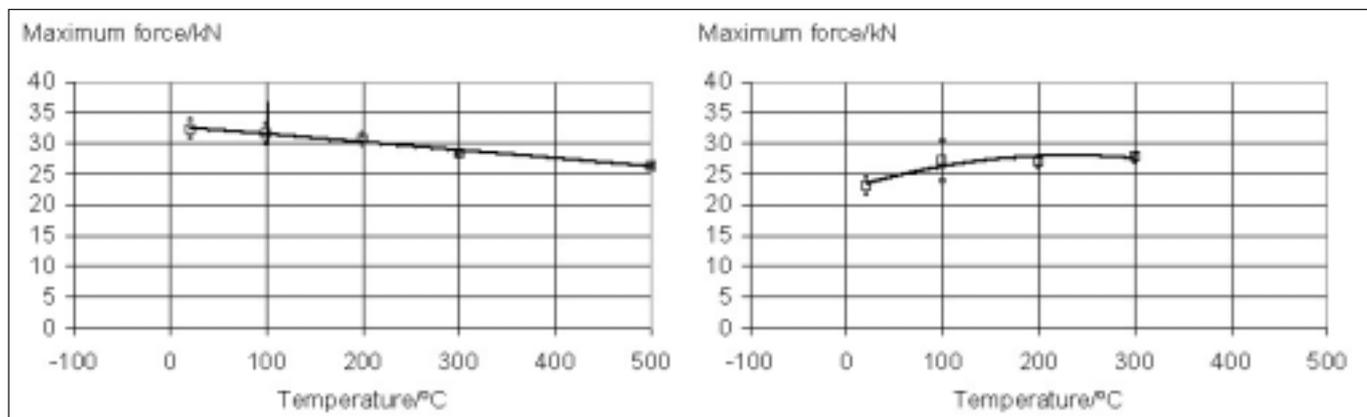


Fig. 15 - Maximum force at impact testing of Dievar 700x300 mm. Austenitizing 30 min at 1030°C, cooling time in the interval 800-500°C 30 s and 1200 s, respectively. Tempering at 615°C to 44 HRC. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 15 – Carico massimo nella prova di impatto dell'acciaio Dievar da 700x300 mm. Austenitizzazione: 30' a 1030°C; raffreddamento nell'intervallo 800-500 °C, 30s e 1200 s rispettivamente. Rinvenimento a 615°C per 44 HRC. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

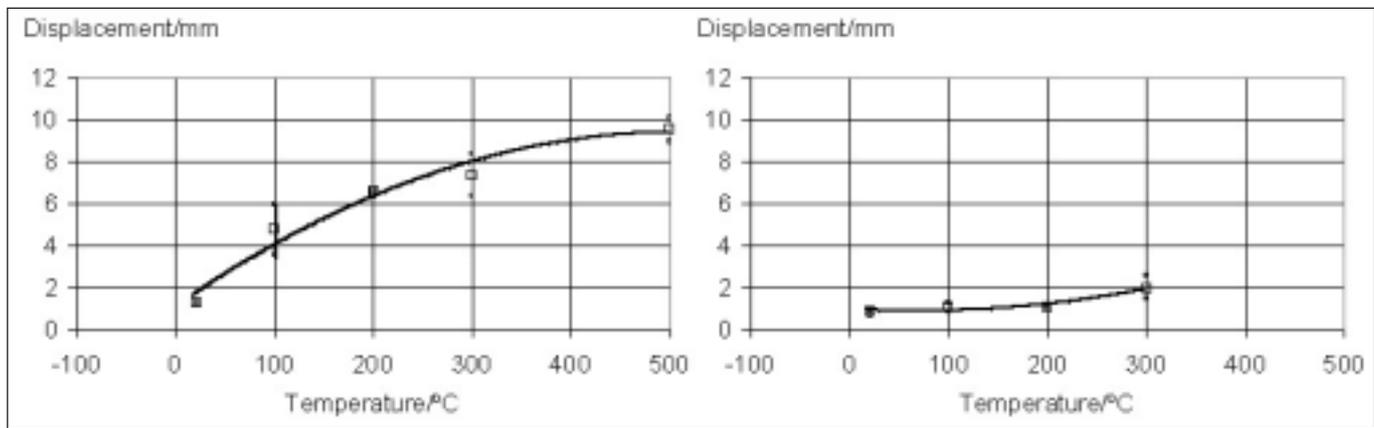


Fig. 16 – Displacement at impact testing of Dievar 700x300 mm. Austenitizing 30 min at 1030°C, cooling time in the interval 800-500°C 30 s and 1200 s, respectively. Tempering at 615°C to 44 HRC. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 16 – Spostamento nella prova di impatto dell'acciaio Dievar da 700x300 mm. Austenitizzazione: 30' a 1030°C; raffreddamento nell'intervallo 800-500 °C, 30s e 1200 s rispettivamente. Rinvenimento a 615°C per 44 HRC. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

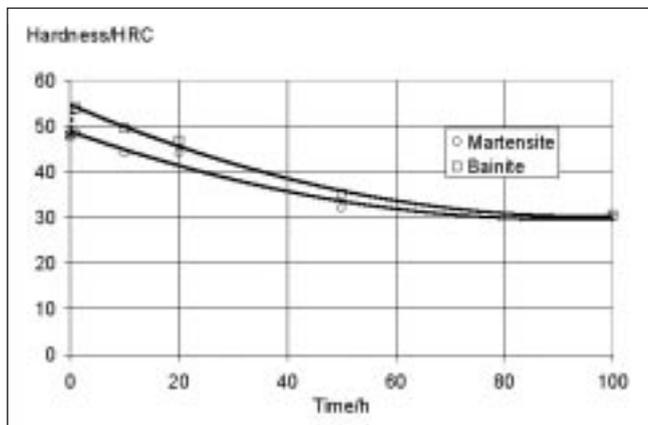


Fig. 17 – Hardness versus time at 600°C for Dievar heat treated to 48 HRC according to table 2.

Fig. 17 – Durezza in rapporto a tempo a 600°C per l'acciaio Dievar trattato a 48 HRC secondo la tabella 2.

He et al [6] studied a chromium-nickel alloyed steel intended for forging dies. They compared fracture toughness and impact toughness of austempered and tempered specimens with quenched and tempered specimens. One of their con-

clusions was that the fracture toughness of tempered lower bainite is higher than the fracture toughness of martensite tempered to equivalent hardness.

In order to see if austempering may be used for Dievar and X40CrMoV5-1 K_{Ic} fracture toughness specimens were quenched and tempered and austempered to the equivalent hardness. After austempering the metallographical structure should consist of lower bainite. Dievar was investigated at two different levels of hardness. At the higher hardness the austempered specimens were not tempered. The result is shown in table 2 and 3.

From table 2 and 3 it is clear that austempering followed by tempering gives considerably lower fracture toughness than quenching and tempering to equivalent hardness. This is valid if the cooling time in the temperature range 800°C to 500°C is equivalent. Table 3 shows that very slow cooling of specimens of Dievar ($t_{800-500°C} = 1270s$) to 48 HRC gives a fracture toughness equivalent to specimens which are cooled at a considerably higher rate ($t_{800-500°C} = 330 s$), austempered and tempered to 46 HRC!

Untempered austempered Dievar has a very high fracture toughness. However untempered steel cannot be used in hot-work applications because the steel is not stable. Figure 17 shows that the hardness of untempered bainite, which is the dominant structure constituent in austempered steel, increa-

Austenitizing	$t_{800-500°C}$	Austempering	Tempering	Hardness	K_{Ic} 90% confidence interv.
1025°C 30 min	380 s	-	600°C 2 h+607°C 2 h	48 HRC	41,1±0,9 [40,2; 42,0] MPa
1020°C 30 min	1270 s	-	600°C 2+2 h	48 HRC	32,2±0,9 [31,3; 33,1] MPa
1025°C 30 min	330 s	300°C 3 h	-	48 HRC	59,9±3,9 [56,0; 63,8] MPa
1025°C 30 min	400 s	-	620°C 2 h+615°C 2 h	45 HRC	55,9±4,2 [51,7; 60,1] MPa
1025°C 30 min	360 s	300°C 3 h	630°C 2+2 h	46 HRC	32,8±2,5 [32,3; 35,3] MPa

Table 2 – Fracture toughness of Dievar 915x407 mm.

Tab. 2 – Valori di K_{Ic} del Dievar (barra da 915x407 mm).

Austenitizing	$t_{800-500°C}$	Austempering	Tempering	Hardness	K_{Ic} 90% confidence interv.
1025°C 30 min	60 s	-	610°C 2+2 h	44 HRC	47,5±1,0 [46,5; 48,5] MPa
1025°C 30 min	60 s	325°C 3 h	615°C 2 h + 620°C 2 h	45 HRC	36,2±2,4 [33,8; 38,6] MPa

Table 3 – Fracture toughness of X40CrMoV5-1 610x153 mm.

Tab. 3 – Valori di K_{Ic} dell'acciaio X40CrMoV5-1 (barra da 610x153 mm).

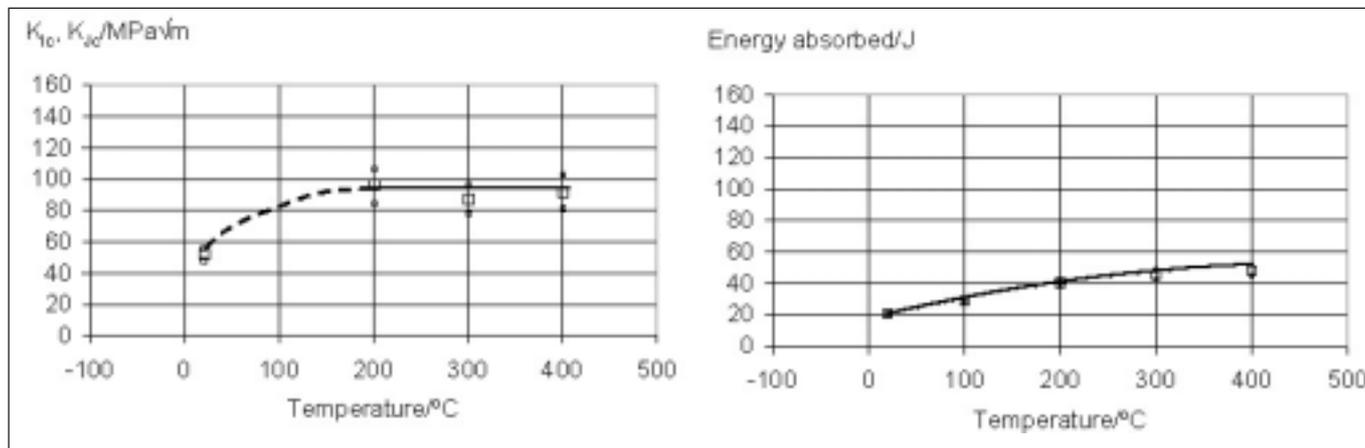


Fig. 18 – Fracture toughness (K_{Ic} at room temperature, K_{Ic0} above room temperature) and impact toughness of X40CrMoV5-1 508x127 mm. 1025°C 30 min, cooling time between 800°C and 500°C 30 s and 70 s, respectively. Tempering 615°C 2+2 h. Hardness: 44-45 HRC. Large symbols indicate mean values and small symbols 90% confidence intervals for the mean.

Fig. 18 – Tenacità alla frattura (K_{Ic} a temperatura ambiente, K_{Ic0} sopra la temperatura ambiente) dell'acciaio X40CrMoV5-1 da 508x127 mm. Austenitizzazione: 30' a 1025°C; raffreddamento da 800° a 500°C, 30s e 70 s rispettivamente. Rinvenimento a 615°C 2+2 h. Durezza 44-45 HRC. I simboli più grandi indicano i valori medi mentre quelli piccoli rappresentano gli intervalli di confidenza del 90%.

ses from 48 HRC to 54 HRC before it begins to decrease if the steel is exposed to 600°C. At lower temperatures, of course, the hardness peaks after a considerable length of time. After long time the hardness of the bainite decreases to the same level as the hardness of the tempered martensite obtained after hardening and tempering

Influence of preheating on the toughness

In order to determine the importance of preheating the influence of the temperature on both Charpy-V notch impact toughness and J_{Ic} fracture toughness have been investigated. In order to make the latter values comparable to the K_{Ic} values above they have been converted to stress intensity values by using formula (3). Such values are designated K_{Jc}

$$K_{Jc}^2 = \frac{J_{Ic} E}{1 - \nu^2} \quad (3)$$

where E is Young's modulus and ν is Poissons's ratio. The results of the research are presented in figure 18. Normal preheating temperature is 200-250°C. The impact toughness at this temperature is twice as high as the impact toughness at room temperature. The difference in fracture toughness between the two temperatures is slightly smaller.

CONCLUSIONS

In order to obtain high toughness in dies and moulds the cooling rate must be sufficiently high during the quenching. The very high impact toughness values obtained in the capability testing carried out at the steel manufacturer are seldom obtained in practice because in these tests impact specimens are generally oil quenched which means that the quenching rate is very high.

If NADCA's recommendation that the quenching rate must not be lower than 28°C/min in the temperature interval 1030°C to 540°C is followed the results in this investigation indicate that the impact toughness of large dies can be up to 40% lower than the capability values given by the steel producers.

As the toughness inevitably will be lower in large dies than in small ones it is of extra importance that large dies are properly preheated.

High cooling rates during quenching increases distortion

and the risk of quenching cracks. Austempering can reduce these risks but gives low impact and fracture toughness. Martempering may be a solution.

The hardness has a strong impact on the toughness. Toughness increases fast with decreasing hardness. In practice however the hardness level is determined by the requirements on resistance against plastic deformation, mechanical fatigue and thermal fatigue.

The energy absorption in impact testing increases in the whole temperature range with decreasing hardness. Instrumented testing revealed that differences in energy absorption between different test materials was mainly a result of differences in displacement. At low energy absorption the impact specimens broke prior to general yielding, that is in a brittle manner. Slow quenching of material gave low energy absorption which had previously resulted in high energy absorption after fast quenching. General yielding and large displacement were replaced by fracture prior to general yielding and small displacement.

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**L'INFLUENZA DEL TRATTAMENTO TERMICO
SULLA TENACITÀ DI ALCUNI ACCIAI DA UTENSILE
PER LAVORAZIONI A CALDO**

**Parole chiave: trattamenti termici,
acciaio, lavorazioni a caldo**

Si è studiata l'influenza del trattamento termico sulla tenacità di alcuni tipi di acciaio da utensile impiegati per esempio nella pressocolata. Sono stati esaminati l'X40CrMoV5-1, l'X37CrMoV5-1 e il Dievar (un nuovo grado di acciaio da utensili per lavorazione a caldo sviluppato da Uddeholm). La resistenza all'impatto è stata valutata a diverse temperature mediante prova convenzionale Charpy su provini con intaglio a V e su provini strumentati, sempre con intaglio a V. La tenacità alla frattura è stata studiata mediante la prova K_{Ic} a temperatura ambiente e la prova J_{Ic} a temperature

elevate. Sono state esaminate sia l'influenza della durezza sia quella della velocità di raffreddamento durante la tempra. Inoltre, è stata misurata la tenacità dopo austempering confrontandola con quella dopo tempra e rinvenimento a parità di valori di durezza. È stata valutata l'influenza del preriscaldamento dello stampo sulla resistenza mediante prove di resistenza all'impatto e alla frattura, a varie temperature. In tutto l'intervallo di temperature si è riscontrata una diminuzione dell'assorbimento di energia nella prova di resilienza all'aumentare della durezza e al diminuire della velocità di tempra. Anche la resistenza alla frattura risulta diminuita se aumenta la durezza e diminuisce la velocità di tempra. Con il processo di austempering seguito da rinvenimento, a parità del valore di durezza, si è ottenuta una tenacità minore rispetto a quella dopo tempra e rinvenimento convenzionali. Il preriscaldamento dello stampo aumenta considerevolmente la resistenza.