

INFLUENCE OF THE COOLING RATE DURING QUENCHING ON THE TOUGHNESS AT TYPICAL WORKING TEMPERATURES OF DIE-CASTING DIES

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The influence of the cooling rate during quenching on the toughness of two hot-work tool steel grades at ambient temperature and at working temperatures typical for die-casting dies has been compared. The heat treatments were performed in a vacuum furnace. Different cooling rates were obtained by varying the nitrogen gas pressure and cooling fan velocity. The impact toughness was researched by conventional and instrumented Charpy V-notch impact testing at various temperatures. The fracture toughness was studied by K_{Ic} fracture toughness testing at room temperature and J_{Ic} fracture toughness testing at elevated temperatures. The researched grades were Uddeholm Vidar Superior (X37CrMoV5-1 with reduced silicon content) and Uddeholm QRO 90 Supreme. The influence of the cooling rate on the toughness differed considerably between ambient and elevated temperatures. The decrease in toughness with decreasing cooling rate was more gradual at elevated temperatures. The reason for the difference was that the fracture type at elevated temperature was fibrous while at room temperature it was more or less completely quasi cleavage.

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

INTRODUCTION

The influence of the cooling rate during quenching on the toughness has been investigated by several researchers e.g. Schmidt [1], Okuno [2, 3] and Yücel et al [4]. With the exception that Schmidt investigated the energy absorption in Charpy V-notch impact testing of X40Cr-Mo-V5-1 at 427°C, all tests were done at ambient temperature. Aluminium die-casting dies are generally preheated to 200-300°C while the preheating temperature for copper alloy die-casting dies is 300-350°C. Room temperature toughness is thus not a relevant measure of the resistance against gross failure of die-casting dies. Therefore toughness testing of two hot-work tool steel grades has been performed at elevated temperatures.

EXPERIMENTATION

The heat treatment of the specimens were made in a Schmetz vacuum furnace with a maximum nitrogen overpressure of 5

bars. The temperature of the specimens was determined by using a type N thermocouple mounted in a dummy specimen. Different cooling rates during quenching were obtained by varying the nitrogen gas pressure and cooling fan velocity. The cooling rate was expressed as the time between 800°C and 500°C.

Toughness was measured by fracture toughness testing, conventional and instrumented Charpy V-notch impact testing. The fracture toughness testing was performed in an MTS 700 kN servo-hydraulic universal testing machine. The ASTM standard for K_{Ic} fracture toughness testing E399-06 [5] and J_{Ic} fracture toughness testing E813-89 [6] were followed. Compact tension (CT) specimens of width W=34 mm and thickness B=17 mm were used. The energy per area values from the J_{Ic} fracture toughness testing were converted to stress intensity values by using equation (1).

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

Charpy V-notch impact testing was performed in a 150 J impact pendulum manufactured by Roell-Amsler. In the conventional tests the energy absorption was calculated from the angles of release and rise of the pendulum. In the instrumented tests the tup that broke the specimens was equipped with strain gauges which allowed the force acting on the specimen during the testing to be calculated. Force versus time curves were thus obtained. The displacement, s, was calculated from the time, t, the force, F, the mass of the pendulum, m, and the initial pendulum velocity, v₀,

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Steel grade	Cross section of bar					
	1000x200 mm		400x250 mm			
Uddeholm Vidar Superior	1000x200 mm		400x250 mm			
Uddeholm QRO 90 Supreme	305x127 mm					
	%C	%Si	%Mn	%Cr	%Mn	%Cr
Uddeholm Vidar Superior	0,36	0,3	0,3	5,0	0,3	5,0
Uddeholm QRO 90 Supreme	0,38	0,3	0,8	2,6	0,8	2,6

Tab. 1

Test material, cross section of the bars and typical chemical composition (weight-%).

Materiale testato, sezione della barra di partenza ed analisi chimica media (peso %).

by a double numeric integration:

$$(2) \quad v(t) = v_0 - \frac{1}{m} \int_{t_0}^t F(t) dt$$

$$(3) \quad s(t) = \int_{t_0}^t v(t) dt$$

where t_0 is time at the beginning of the deformation.

In this way force versus displacement curves instead of force versus time curves were obtained.

The energy values were calculated from the area under the curves. According to EN ISO 14556:2000 [7] force-displacement curves are

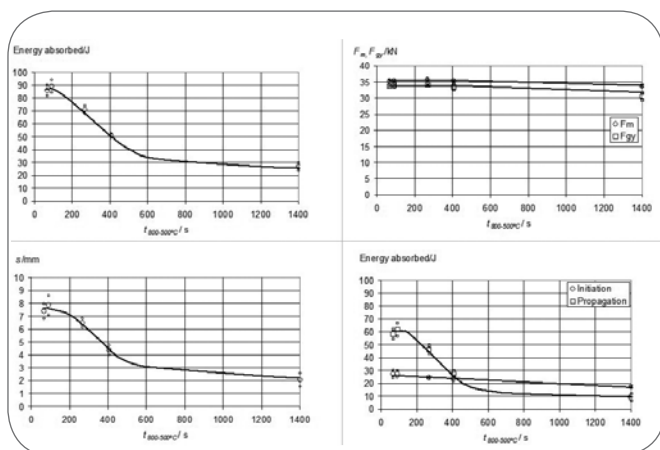


Fig. 1

Influence of the cooling rate during quenching expressed as the time between 800°C and 500°C on the total energy absorption, general yield force, maximum force, displacement, energy required for crack initiation and energy required for crack propagation at 200°C of Uddeholm Vidar Superior. Austenitizing 1000°C 30 min, quenching at various rates and tempering 600°C

2+2 h. Hardness: 47-49 HRC. Mean values and 99% confidence intervals for the mean values.

Influenza della velocità di raffreddamento durante la tempra, espressa come tempo nell'intervallo fra 800°C e 500°C, sull'energia totale assorbita, sulla forza a snervamento, sulla forza massima, sulla deformazione, sull'energia necessaria per l'innesco della frattura e sull'energia per la propagazione della frattura a 200°C nelle prove di resilienza strumentate Charpy V effettuate su provini di Uddeholm Vidar Superior 1000x200 mm. Austenizzazione a 1000°C per 30 min, raffreddamento a varie velocità e rinvenimento a 600°C per 2+2 ore. Durezza: 47-49 HRC. Valori medi con intervalli di confidenza del 99%.

classified into six different types. Several characteristic values of the energy, force and displacement can be determined. In this presentation the curve types are not discussed at all. The presented results from the testing are total energy, energy required for crack initiation, energy required for crack propagation, maximum force (F_m), general yield force (F_{gy}) and maximum displacement (s).

TEST MATERIAL

Cross section and typical chemical composition of the test materials, Uddeholm Vidar Superior (X37CrMoV5-1 with reduced silicon content) and Uddeholm QRO 90 Supreme, are shown in Tab. 1. The specimens were cut from the centre of the bar in such a way that the direction 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 is designated S-T. The number of specimens in the tests generally varied between three and twelve.

TEST RESULTS AND DISCUSSION

Uddeholm Vidar Superior

Fig. 1 reveals that the total energy decreased gradually with increasing cooling time. The energy required for crack initiation changed very slowly so the decrease in total energy absorption was almost entirely a consequence of the decrease in the energy required for crack propagation. This, in turn, was a consequence of a decrease in displacement as the force changed very little. General yielding occurred for all cooling rates.

Fig. 2 reveals that the same steel behaved completely differently at room temperature. General yielding only occurred in the fastest quenched specimens. The total energy decreased substantially between 60 s and 110 s. Between 200 s and 400 s there was no influence of the cooling rate on the energy absorption. At cooling times longer than 400 s the energy absorption decreased again. The energy required for propagation changed very little with increasing cooling time so the decrease was a consequence of the decrease in initiation energy. This decrease was, in turn, a consequence of the decrease in displacement and force. The fracture was initiated as a fibrous one in the fastest cooled specimens. With increasing cooling time the fracture type changed to cleavage. Below the initiation area the fracture type was always quasi cleavage.

The decrease in fracture toughness at 200°C was substantially smaller than the decrease in energy absorption in the Charpy V-notch impact testing, see Fig. 3. The fracture toughness at room temperature changed in a similar manner as the energy absorption changed at room temperature, see Fig. 4. The decrease between 400 s and 600 s was more pronounced, though.

Fig. 5 and 6 reveal that above 200°C the toughness did not increase at all or very slowly with increasing temperature. However, the specimens were ideally heat treated. Slow quenching probably moves the transition curve towards higher temperature, see next section.

Uddeholm QRO 90 Supreme

Fig. 7 and 8 reveal that also the decrease in energy absorption of Uddeholm QRO 90 Supreme at 300°C was more gradual than at ambient temperature. At 300°C general yielding occurred for all cooling times and neither the maximum force nor the general yield force changed with increasing cooling time. The initiation energy was constant so the decrease in total energy absorption was entirely

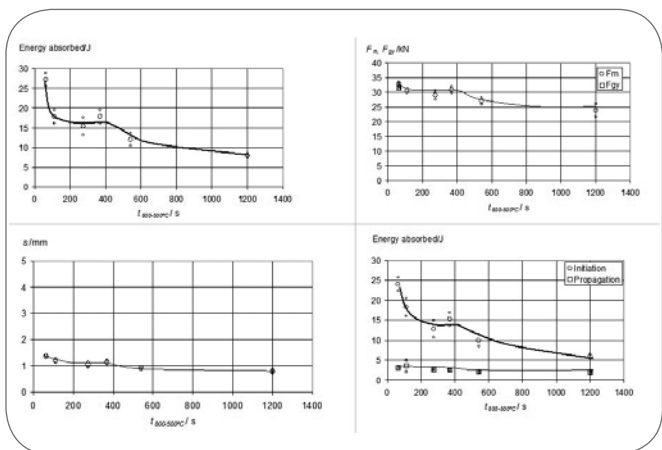


Fig. 2

Influence of the cooling rate during quenching expressed as the time between 800°C and 500°C on the total energy absorption, general yield force, maximum force, displacement, energy required for crack initiation and energy required for crack propagation of Uddeholm Vidar Superior 1000x200 mm. Austenitizing 1000°C 30 min, quenching at various rates and tempering 600°C 2+2 h. Hardness: 45-46 HRC. Mean values and 99% confidence intervals for the mean values.

Influenza della velocità di raffreddamento durante la tempra, espressa come tempo nell'intervallo fra 800°C e 500°C, sull'energia totale assorbita, sulla forza a snervamento, sulla forza massima, sulla deformazione, sull'energia necessaria per l'innesco della frattura e sull'energia per la propagazione della frattura a temperatura ambiente nelle prove di resilienza strumentate Charpy V effettuate su provini di Uddeholm Vidar Superior 1000x200 mm. Austenizzazione a 1000°C per 30 min, raffreddamento a varie velocità e rinvenimento a 600°C per 2+2 ore. Durezza: 45-46 HRC. Valori medi con intervalli di confidenza del 99%.

a consequence of a decrease in propagation energy. The decrease in propagation energy was, in turn, due to the decrease in displacement.

The fracture was always initiated as a fibrous one which is what can be expected as the initiation energy was constant. Below the initiation area the amount of fibrous fracture decreased with increasing cooling time and was replaced by quasi cleavage fracture.

At ambient temperature the total energy absorption was constant up to a cooling time of between 800°C and 500°C of slightly more than 100 s. Then it decreased fast with increasing cooling time up to about 300 s when a lower shelf value was reached. General yielding never occurred. The steel thus behaved elastically. The energy required for crack propagation was small and almost independent of the cooling time. The decrease of the total energy was thus entirely a consequence of a decrease in the energy required for crack initiation. This decrease was due to a simultaneous decrease in maximum force and displacement.

The fracture type at ambient temperature was quasi cleavage for all cooling times.

The transition curves for ideally heat treated specimens and specimens quenched so that the cooling time between 800°C and 500°C was 400 s are shown in Fig. 9 and 10. The energy absorption of the fast quenched specimens was higher than the slower quenched specimens up to 300°C. The difference is a consequence of differences in the propagation energy which in turn is due to the difference in displacement. The explanation for this is that the fracture type below the initiation area of the fast quenched specimens changed

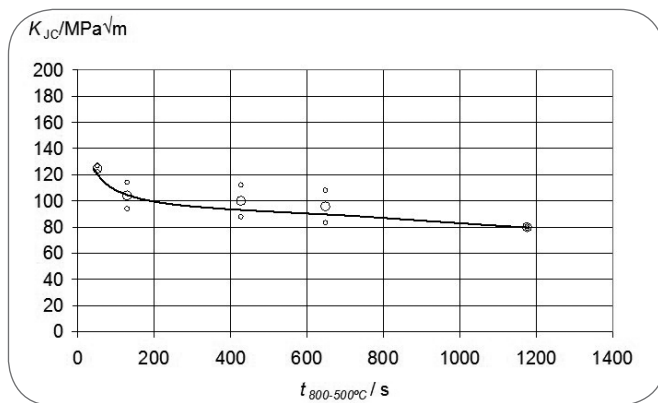


Fig. 3

Influence of the cooling rate during quenching expressed as the time between 800°C and 500°C on the fracture toughness at 200°C of Uddeholm Vidar Superior. Austenitizing 1000°C 30 min, quenching at various rates and tempering 600°C 2+2 h. Hardness: 45 HRC. Mean values and 90% confidence intervals for the mean values.

Influenza della velocità di raffreddamento durante la tempra, espressa come tempo nell'intervallo fra 800°C e 500°C, sulla tenacità a frattura a 200°C di provini di Uddeholm Vidar Superior 400x250 mm. Austenizzazione a 1000°C per 30 min, raffreddamento a varie velocità e rinvenimento a 600°C per 2+2 ore. Durezza: 45 HRC. Valori medi con intervalli di confidenza del 90% per i valori medi.

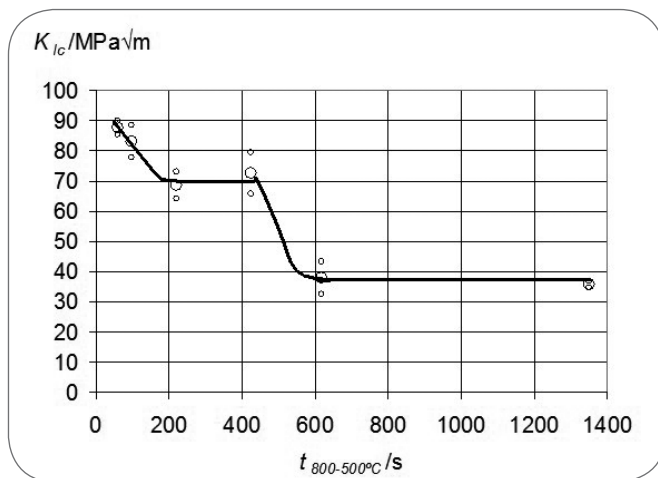


Fig. 4

Influence of the cooling rate during quenching expressed as the time between 800°C and 500°C on the fracture toughness of Uddeholm Vidar Superior 1000x200 mm. Austenitizing 1000°C 30 min, quenching at various rates and tempering 600°C 2+2 h (420 s and 1350 s: +605°C 2 h). Hardness: 47-48 HRC. Mean values and 90% confidence intervals for the mean values.

Influenza della velocità di raffreddamento durante la tempra, espressa come tempo nell'intervallo fra 800°C e 500°C, sulla tenacità a frattura a temperatura ambiente di provini di Uddeholm Vidar Superior 1000x200 mm. Austenizzazione a 1000°C per 30 min, raffreddamento a varie velocità e rinvenimento a 600°C per 2+2 ore (420 s e 1350 s: +605°C per 2 ore). Durezza: 47-48 HRC. Valori medi con intervalli di confidenza del 90% per i valori medi.

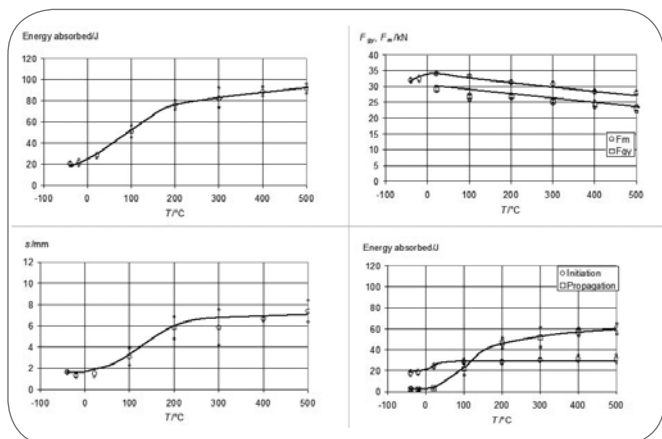


Fig. 5

Influence of the temperature on the energy absorption, general yield force, maximum force, displacement, energy required for crack initiation and energy required for crack propagation of Uddeholm Vidar Superior 1000x200 mm. Austenitizing 1000°C 30 min, cooling time between 800°C and 500°C: 30 s, and tempering 600°C 2+2 h. Hardness: 45 HRC. Mean values and 90% confidence intervals for the mean values.

Influenza della temperatura sull'energia assorbita, sulla forza a snervamento, sulla forza massima, sulla deformazione, sull'energia necessaria per l'innesco della frattura e sull'energia per la propagazione della frattura nelle prove di resilienza strumentate Charpy V effettuate su provini di Uddeholm Vidar Superior 1000x200 mm. Austenizzazione a 1000°C per 30 min, tempo di raffreddamento nell'intervallo fra 800°C e 500°C: 30 s e rinvenimento a 600°C per 2+2 ore. Durezza: 45 HRC. Valori medi con intervalli di confidenza del 90% per i valori medi.

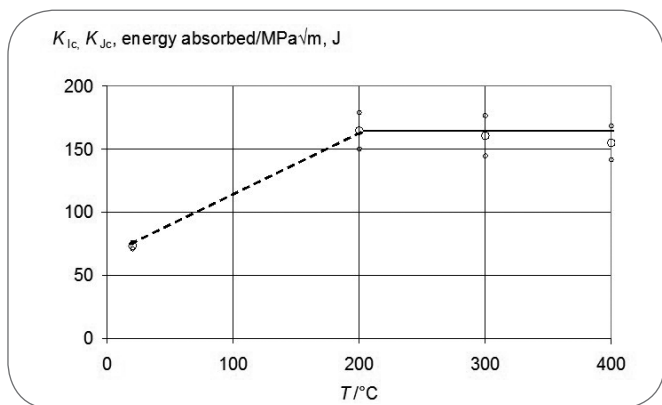


Fig. 6

Influence of the temperature on the fracture toughness of Uddeholm Vidar Superior. Austenitizing 1000°C 30 min, cooling time between 800°C and 500°C: 30 s, and tempering 600°C 2+2 h. Hardness: 45 HRC. Mean values and 90% confidence intervals for the mean values. Testing at 100°C failed due to unstable crack growth.

Influenza della temperatura sulla tenacità a frattura dell'acciaio Uddeholm Vidar Superior. Austenizzazione a 1000°C per 30 min, tempo di raffreddamento nell'intervallo da 800°C a 500°C: 30 s e rinvenimento a 600°C per 2+2 ore. Durezza: 45 HRC. Valori medi con intervalli di confidenza del 90% per i valori medi. Prova a 100°C non completata a causa di una propagazione non stabile della cricca.

from quasi cleavage to fibrous between ambient temperature and 100°C. In the slower quenched specimens this occurred between 100°C and 200°C. General yielding began to occur in the same temperature ranges. This explains why the maximum force was higher in the fast quenched specimens at room temperature and 100°C but not at higher temperatures.

DISCUSSION

Uddeholm QRO 90 Supreme had lower energy absorption in Charpy V-notch impact testing than had Uddeholm Vidar Superior. When used at ambient temperature QRO 90 Supreme requires very fast cooling during quenching in order to obtain reasonable toughness values. For dies other than very small ones and core pins the grade is suitable in applications where the die can be preheated to about 300°C. The reason why Uddeholm Vidar Superior manages slower cooling than does Uddeholm QRO 90 Supreme is the much better hardenability, compare Fig. 9 and 10. The low hardenability of Uddeholm QRO 90 Supreme is a concession for the good thermal conductivity. In order to obtain high thermal conductivity the amount of alloying elements such as chromium must be restricted. Uddeholm QRO 90 Supreme has about 30% higher thermal conductivity than has Uddeholm Vidar Superior. Fig. 12 reveals that Uddeholm QRO 90 Supreme has additional advantages. The creep resistance expressed as the stress required to obtain 1% elongation is about five times longer for Uddeholm QRO 90 compared with Uddeholm Vidar Superior. Both at 550°C and 600°C about seven times longer time is required to decrease the hardness of QRO 90 Supreme from 45 HRC to 40 HRC compared with Uddeholm Vidar Superior. The North American Die Casting Association (NADCA) recom-

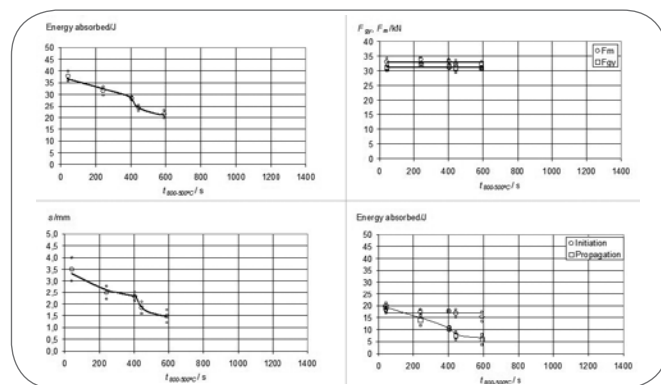


Fig. 7

Influence of the cooling rate during quenching expressed as the time between 800°C and 500°C on the energy absorption, general yield force, maximum force, displacement, energy required for crack initiation and energy required for crack propagation of Uddeholm QRO 90 Supreme at 300°C. Austenitizing 1030°C 30 min, quenching at various rates and tempering 620°C 2+2 h. Hardness 47-48 HRC.

Influenza della velocità di raffreddamento durante la tempra, espressa come tempo nell'intervallo fra 800°C e 500°C, sull'energia totale assorbita, sulla forza a snervamento, sulla forza massima, sulla deformazione, sull'energia necessaria per l'innesco della frattura e sull'energia per la propagazione della frattura a 300°C nelle prove di resilienza strumentate Charpy V effettuate su provini di Uddeholm QRO 90 Supreme. Austenizzazione a 1030°C per 30 min, raffreddamento a varie velocità e rinvenimento a 620°C per 2+2 ore. Durezza: 47-48 HRC. Valori medi con intervalli di confidenza del 99%.

mends a minimum quench rate of 28°C/min for H11 (X37CrMoV5-1) in the temperature range 1030-540°C [8]. Internal research has shown that the cooling rate between 1030°C and 540°C roughly corresponds to the same rate in the interval between 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. At cooling times longer than about 600 s a lower shelf toughness value is reached.

CONCLUSIONS

Room temperature toughness is not a relevant measure of the resistant against gross cracking of die-casting dies. The influence of the cooling rate during quenching on the toughness differs considerably between ambient temperature and typical preheating temperatures.

Slow cooling promotes quasi cleavage fracture which moves the transition curve towards a higher temperature. The change of fracture type from quasi cleavage to fibrous when the temperature is increased from ambient temperature to typical preheating temperatures also explains the change in the influence of the cooling rate during quenching on the toughness. The sharp decrease in toughness at room temperature of Uddeholm Vidar Superior at a cooling time between 800°C and 500°C of about 400 s is due to the formation of bainite. The corresponding drop in toughness of Uddeholm QRO 90 Supreme occurs at slightly longer time than 100 s. At typical preheating temperatures the decrease in toughness with decreasing cooling rate is more gradual than at room temperature.

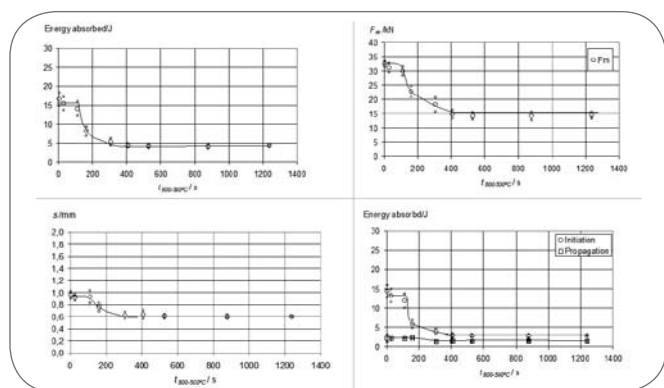


Fig. 8 Influence of the cooling rate during quenching expressed as the time between 800°C and 500°C on the total energy absorption, the maximum force, the displacement and the energy required for crack initiation and crack propagation in instrumented Charpy V-notch impact testing of Uddeholm QRO 90 Supreme 305x127 mm. Austenitizing: 30 min at 1030°C, quenching at various rates and tempering 620°C 2+2 h. Hardness 47-48 HRC. Mean values and 99% confidence intervals for the mean values.

Influenza della velocità di raffreddamento durante la tempra, espressa come tempo nell'intervallo fra 800°C e 500°C, sull'energia totale assorbita, sulla forza massima, sulla deformazione, sull'energia necessaria per l'innesco della frattura e sull'energia per la propagazione della frattura a temperatura ambiente nelle prove di resilienza strumentate Charpy V effettuate su provini di Uddeholm QRO 90 Supreme 305x127 mm. Austenizzazione a 1030°C per 30 min, raffreddamento a varie velocità e rinvenimento a 620°C 2+2 ore. Durezza: 47-48 HRC. Valori medi con intervalli di confidenza del 99%.

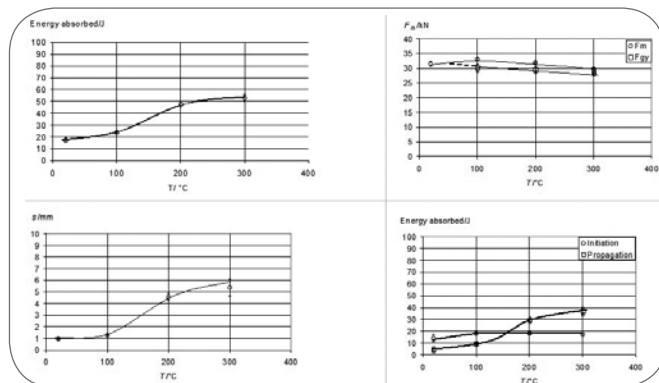


Fig. 9 Influence of the temperature on the total energy absorption, the maximum force, the displacement and the energy required for crack initiation and crack propagation in instrumented Charpy V-notch impact testing of Uddeholm QRO 90 305x127 mm. Austenitizing: 1030°C 30 min, cooling time between 800°C and 500°C: 40 s and tempering: 650°C 2+2 h. Hardness: 43 HRC. 90% confidence intervals for the mean values.

Influenza della temperatura sull'energia totale assorbita, sulla forza massima, sulla deformazione, sull'energia necessaria per l'innesco della frattura e sull'energia per la propagazione della frattura nelle prove di resilienza Charpy V strumentate effettuate su provini di Uddeholm QRO 90 305x127 mm. Austenizzazione a 1030°C per 30 min, tempo di raffreddamento fra 800°C e 500°C: 40 s e rinvenimento a 650°C per 2+2 ore. Durezza: 43 HRC. Valori medi con intervalli di confidenza del 90%.

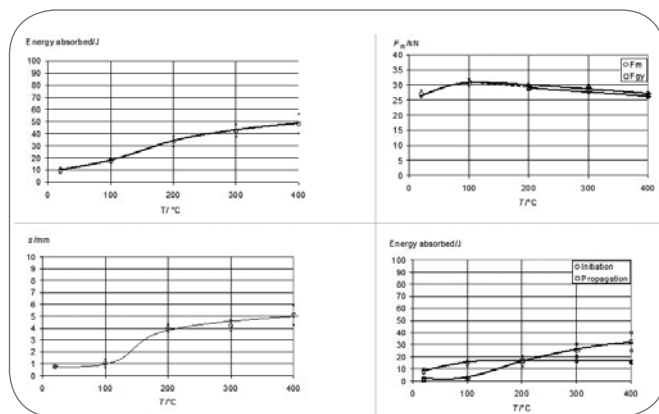


Fig. 10 Influence of the temperature the total energy absorption, the maximum force, the displacement and the energy required for crack initiation and crack propagation in instrumented Charpy V-notch impact testing of Uddeholm QRO 90 305x127 mm. Austenitizing: 1030°C 30 min, cooling time between 800°C and 500°C: 400 s and tempering: 650°C 2+2 h. Hardness: 43 HRC. 90% confidence intervals for the mean values.

Influenza della temperatura sull'energia totale assorbita, sulla forza massima, sulla deformazione, sull'energia necessaria per l'innesco della frattura e sull'energia per la propagazione della frattura nelle prove di resilienza Charpy V strumentate effettuate su provini di Uddeholm QRO 90 305x127 mm. Austenizzazione a 1030°C per 30 min, tempo di raffreddamento fra 800°C e 500°C: 400 s e rinvenimento a 650°C per 2+2 ore. Durezza: 43 HRC. Valori medi con intervalli di confidenza del 90%.

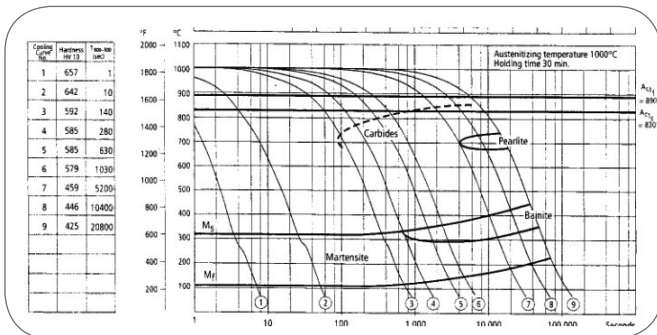


Fig. 11
CCT diagram of Uddeholm Vidar Superior.
 Diagramma CCT dell'acciaio Uddeholm Vidar Superior.

The North American Die Casting Association's (NADCA's) recommended minimum quench rate is reasonable for X37CrMoV5-1. Lower quench rate than the recommended one gives very poor toughness. It is extremely important to preheat dies of Uddeholm QRO 90 Supreme as the ambient temperature toughness is very low for cooling times exceeding 100 s.

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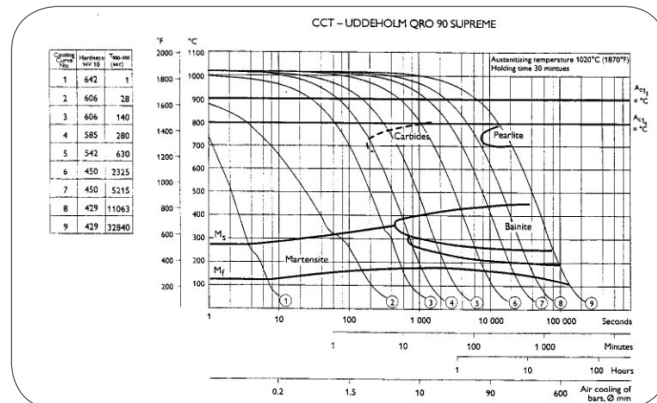


Fig. 12
CCT diagram of Uddeholm QRO 90 Supreme.
 Diagramma CCT dell'acciaio Uddeholm QRO 90 Supreme.

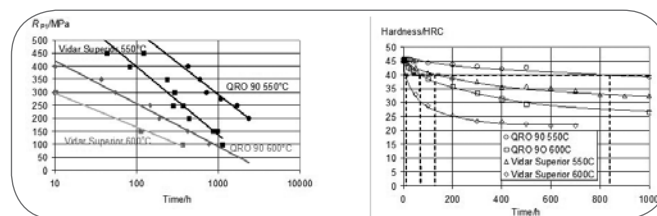


Fig. 13
Creep strength expressed as the stress required to obtain 1% elongation (Rp1) versus time and tempering resistance of Uddeholm Vidar Superior and Uddeholm QRO 90 Supreme.
 Creep strength expressed as the stress required to obtain 1% elongation (Rp1) versus time and tempering resistance of Uddeholm Vidar Superior and Uddeholm QRO 90 Supreme.

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ABSTRACT

INFLUENZA DELLA VELOCITÀ DI RAFFREDDAMENTO DURANTE LA TEMpra SULLA TENACITÀ ALLE TEMPERATURE TIPICHE DEGLI STAMPI PER PRESSOCOLATA

Keywords:

L'influenza della velocità di spegnimento durante la tempra sulla tenacità degli acciai per lavorazione a caldo è stata analizzata da diversi studiosi.

Generalmente si è misurata la tenacità a temperatura ambiente. Tuttavia la temperatura di lavoro di stampi ad esempio per pressocolata di Alluminio è tipicamente di circa 200-300°C. E' pertanto più pertinente la misurazione della tenacità a queste temperature quando si studia l'influenza della velocità di raffreddamento durante la tempra sulla tenacità.

Nello studio sono stati inclusi tre acciai per lavorazione a caldo. Sono stati temprati in un forno in vuoto alcuni campioni intagliati per prova di resilienza Charpy-V e alcuni campioni per test di tenacità a frattura.

Dopo il raggiungimento della temperatura di austenitizzazione i campioni sono

stati raffreddati con diverse velocità, usando differenti pressioni di Azoto e parametri del forno. Successivamente i campioni sono stati rinvenuti in forno a muffola.

Alcuni dei test di resilienza su provini intagliati Charpy-V sono stati eseguiti con pendoli strumentati. Nella prova di tenacità a frattura a temperatura ambiente è stato effettuato il test K_{1c}. Nella prova di tenacità a frattura ad elevate temperature è stato effettuato il test J_{1c}, ed i risultati sono stati convertiti in valori di intensità di sollecitazione.

Entrambi i test di tenacità a frattura rivelano che la diminuzione della tenacità associata alla riduzione della velocità di raffreddamento è più graduale a temperature elevate rispetto che a temperatura ambiente. Ancora a temperature elevate comunque basse velocità di raffreddamento provocano sostanziali abbassamenti di tenacità.

Dalla consistente differenza che esiste tra i valori di tenacità a temperatura ambiente e quelli ad elevate temperature si può concludere che un corretto preriscaldamento degli stampi è estremamente importante per prevenire il rischio di rotture in produzione.