

Notch Toughness in Hot-Rolled Low Carbon Steel Wire Rod

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(Submitted 21 July 1999; in revised form 17 August 1999)

Charpy V-notch toughness has been investigated in four hot-rolled, low carbon steels with different grain sizes and carbon contents between 0.019 and 0.057%. The raw material was wire rod designed for drawing and possible subsequent cold heading operations and manufactured from continuous cast billets. In this study, the influence of microstructure, mechanical properties, and alloying elements on the ductile-brittle transition behavior has been assessed. A particular emphasis has been given to the influence of boron with contents up to 0.0097%.

As a result, transition temperatures between –29 and +50 °C explicated by the material properties have been obtained. The examination also shows that the transition temperature raises with circa 0.5 °C for each added ppm boron most likely as a consequence of an enlargement of the ferrite grain size and the reduction of yield and tensile strength. The highest upper shelf energy and lowest transition temperature can be observed in a steel without boron additions and with maximum contents of carbon, silicon, and manganese.

Keywords boron effect, low carbon steel wire rod, notch toughness

1. Introduction

The toughness of a metal can be defined as the intrinsic ability to absorb mechanical energy and deform plastically before fracturing. The fracture mechanisms of metals under applied stress can be classified into shear, cleavage, intercrystalline fracture, and fatigue (Ref 1). The Charpy V-test procedure was developed in 1909 for evaluation of the transition behavior with two significant measures for predisposition to brittle fracture, namely strain concentrating notch and high loading velocity (Ref 2). The notch toughness has so far been established as an important parameter for material selection in structures subjected to impulsive loading at low temperatures. The carbon content, alloying elements, gas content, and impurities are the main chemical factors acting on this property. The main physical factors are hardness, microstructure, grain size, section size, rolling direction, hot or cold working temperatures, and methods of fabrication. Surface conditions, such as carburization or decarburization, are also important (Ref 2). Because transition temperatures based on either energy absorption, ductility, or fracture appearance criteria do not always agree for the same material, unconsidered utilization of test results in engineering design calculations is therefore not reasonable.

1.1 Cleavage

Brittle fracture comprises at least two stages, namely that of crack initiation and crack propagation. Several explanatory models have been developed for both stages during the 20th century (Ref 3). Generally, cleavage cracking can occur on certain atomic planes through the crystals or along the grain boundaries with little or no prior plastic deformation, often at nominal calculated stresses below the yield point of the material. The resulting fracture surface has a silky or fibrous appearance. In ferrite, cleavage proceeds through the grains along lattice planes (100) with approximately the speed of sound (Ref 3).

In body-centered cubic (bcc) metals, such as ferritic alloys, the yield strength (R_{eL}) is far more sensitive to temperature and strain rate changes than it is in face-centered cubic (fcc) metals, such as aluminum, nickel, copper, and austenitic steel alloys (Ref 4). In bcc metals, at room temperature and below, the fracture occurs preferably by partitioning along lattice planes instead of the grain boundaries as a consequence of a lower cleavage fracture strength, σ_f, than intergranular fracture strength in the material.

In low-strength ferritic steels the mechanism is cleavage at low temperatures and void coalescence at high temperatures. The decisive stage for the cleavage fracture process is assumed to be the propagation of microcracks nucleated at grain boundary carbides under the influence of dislocation pileup (Ref 5). Because cleavage is verified by the macroscopical behavior, that is, the energy used for breaking the test sample, the fracture surface may appear either as brittle or ductile. A macroscopically ductile fracture, proceeding by nucleation, growth, and microvoid coalescence is always microscopically ductile (Ref 4). Because a direct correlation does not always exist between a given fracture mechanism and the magnitude of fracture energy, it is sensible to treat the two terms separately.

1.2 Transition Temperature

The amendment in the absorbed energy values is accompanied by a transition in fracture appearance from 100% shear to 100% cleavage. The magnitude and abruptness of the change in notch toughness that occurs with a temperature change depends on chemical and physical characteristics of the metal. On a closer consideration the impact energy curve shows

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two different steps, a lower step referred to as initiation transition temperature and an upper step referred to as propagation transition temperature (Ref 3). The type of fracture depends strongly on the yield strength, that is, the minimum stress that will lead to a plastic deformation and to a first approximation. The relative notch sensitivity of a given material can be estimated from the yield to tensile-strength ratio, R_{eL}/R_m (Ref 4).

At the notch impact test the transition temperature can be defined according to alternative criteria. It can be defined either as the mean temperature for the corresponding upper and lower shelves in the impact energy curve, or it can be fixed at a point where the notch toughness reaches a given energy value, for example, 27 J. The first empirical impact-energy criterion (21 J) for transition temperature has been completed by other limitations (27 J, 40 J) depending on the yield strength in steel (Ref 2). Specified by the fracture appearance transition temperature (FATT) criterion, transition occurs at a temperature where 50% of the shear lip is brittle.

1.3 Charpy V-Notch Toughness

It can further be shown that the influence of the temperature on the fracture behavior depends on a dissimilarity between the temperature dependence of the yield strength and the fracture strength. The fracture strength increased only nominally as the temperature decreased due to an unchangeable Young's modulus of elasticity and surface energy (Ref 3). Conversely, the yield strength is multiplied many times over in fcc metals, when the temperature is decreased from, for example, +20 to –196 °C. According to Fig. 1 (Ref 3), the cleavage fracture strength decreases with an increasing grain size steeper as the yield strength.

The fracture resistance of a hot-rolled component can be enhanced considerably when the rolling flow lines are oriented parallel to major stress trajectories and normal to the path of a potential crack. The mechanical fibering involves not only alignment of grains but also alignment of inclusions (Ref 4). Charpy V-notch transition curves show that rimmed steels have the highest transition temperatures, killed steels show the lowest transition temperatures, and semikilled grades are intermediate (Ref 1).

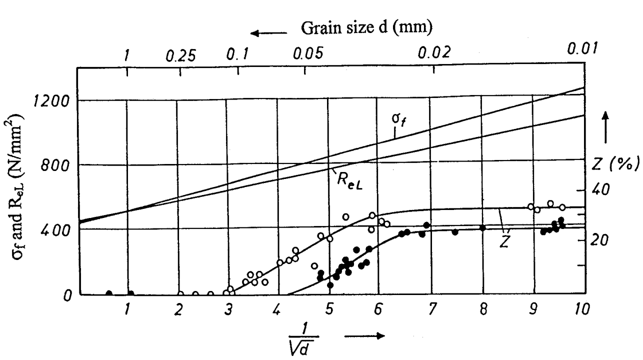

Fig. 1 Relationship between ferrite cleavage fracture strength, σ_f, lower yield point, R_{eL}, reduction of area at fracture, Z, and grain size d at temperature –196 °C. Open circle data point stands for iron; closed circle data point represents a low carbon steel (Ref 3).

Some deficiencies of the Charpy V-test method have been noted due to limitations caused by the small dimensions of standard impact specimens (Ref 3). The energy needed for crack initiation is relatively high below transition, and the energies used up by initiation and propagation are hard to discriminate due to a change over in the internal state of stress. Thus, the reliability and accuracy of the standard Charpy V-test is today appropriate for continual impact testing in connection with quality control routines.

1.4 Alloying Effects

Even small carbon amounts increase transition temperature and decrease upper-shelf fracture energy of iron, especially in the absence of other alloying elements as manganese. For maximum toughness the carbon content should be kept as low as possible. Silicon in amounts of 0.15 to 0.30% lowers transition temperature and improves notch toughness due to higher steel cleanness (Ref 2, 6). Manganese, up to about 1.5%, lowers transition temperature with about 6 °C per 0.10%, and it has no significant effect on maximum energy or the shape of the transition curve (Ref 6).

For rimmed, semikilled, and silicon-killed steels, sulfur in amounts up to about 0.04% apparently has a negligible effect on the low temperature properties and notch toughness. Phosphorus raises transition temperature with 7 °C per 0.01% P and reduces maximum energy absorption (Ref 6).

Vanadium, niobium, and titanium improve toughness primarily by refining the ferrite grain size. Also for aluminum used in addition to silicon for the deoxidation of steel, the amount usually added (0.02 to 0.04%) appears to have a beneficial effect on notch toughness because of grain size control (Ref 6).

The influence of boron additions up to 0.001% seems to raise the transition temperature (Ref 2). It can be shown that it reduces the toughness of as-rolled, as-annealed, and as-normalized steels, and an increased toughness is attained with boron in quenched and tempered products (Ref 6). According to Ref 7, boron additions up to 24 ppm in extra low carbon, high-strength titanium- and niobium-added cold-rolled steels enhances the resistance to brittle fracture.

2. Experimental Procedures

The Fundia Dalsbruk wire rod mill produces nonalloyed or lightly alloyed steel wire rods within a diameter range of 5.5 to 21.0 mm diameter and a carbon range of 0.02 to 0.85%. The production of wire rod containing low levels of residual elements, such as chromium, nickel, and copper is enabled by a basic oxygen steelmaking process (BOF), utalizing hot metal reduced from iron ore pellets. The main influential factors for the mechanical properties in the wire rod are the contents of alloying elements and the temperature progress during hot rolling and cooling.

2.1 Materials

According to the equilibrium boundaries in the Fe-Fe_3C system, the eutectoid reaction ($\alpha \rightarrow \gamma + Fe_3C$) does not occur in ferritic steels with carbon contents below 0.034%. The investigated steels 1 to 3 represent hot-rolled and Stelmor-cooled semikilled ferritic rimming substitute grades used in fine wire drawing and cold rolling for a broad range of industrial products.

The content of typical alloying elements in steel is controlled to a level as low as possible, and the ore-based process route enables steel production with low contents of unwanted metal impurities (<0.06% Cr, <0.1% Ni, and <0.06 Cu). Table 1 presents the chemical compositions of the investigated steels.

Boron influences on the α-grain size in steel by affecting the $\gamma \rightarrow \alpha$ transformation kinetics. In steels 1 to 3 the α-grain size is enlarged, and R_{eL} and R_m are decreased due to a boron addition of 0.011 aim. Steel 4 was a plain low carbon, type SAE 1008 drawing grade. Individual inclusions present typically consist of combinations of MnAlCa silicates mainly composed of Al_2O_3, CaO, and MnO with typical total magnitudes of 3 μm.

In rimming substitute grades, the α-grain size decreased 0.2 ASTM units for each added ppm boron. Consequently, yield

Table 1 Chemical composition in the casts investigated

Steel No.	Composition, wt%														
	C	Si	Mn	P	S	Cr	Mo	Ni	V	Ti	Cu	Al_{tot}	Al_m	B	N
1	0.019	0.010	0.18	0.008	0.007	0.034	0.001	0.037	0.013	0.001	0.011	0.003	0.002	0.0097	0.0028
2	0.020	0.010	0.14	0.009	0.010	0.030	0.001	0.046	0.007	0.001	0.010	0.003	0.002	0.0095	0.0034
3	0.022	0.008	0.16	0.014	0.008	0.027	0.001	0.034	0.017	0.001	0.004	0.004	0.003	0.0043	0.0029
4	0.057	0.094	0.46	0.009	0.011	0.027	0.001	0.035	0.014	0.001	0.016	0.003	0.002	0.0001	0.0037

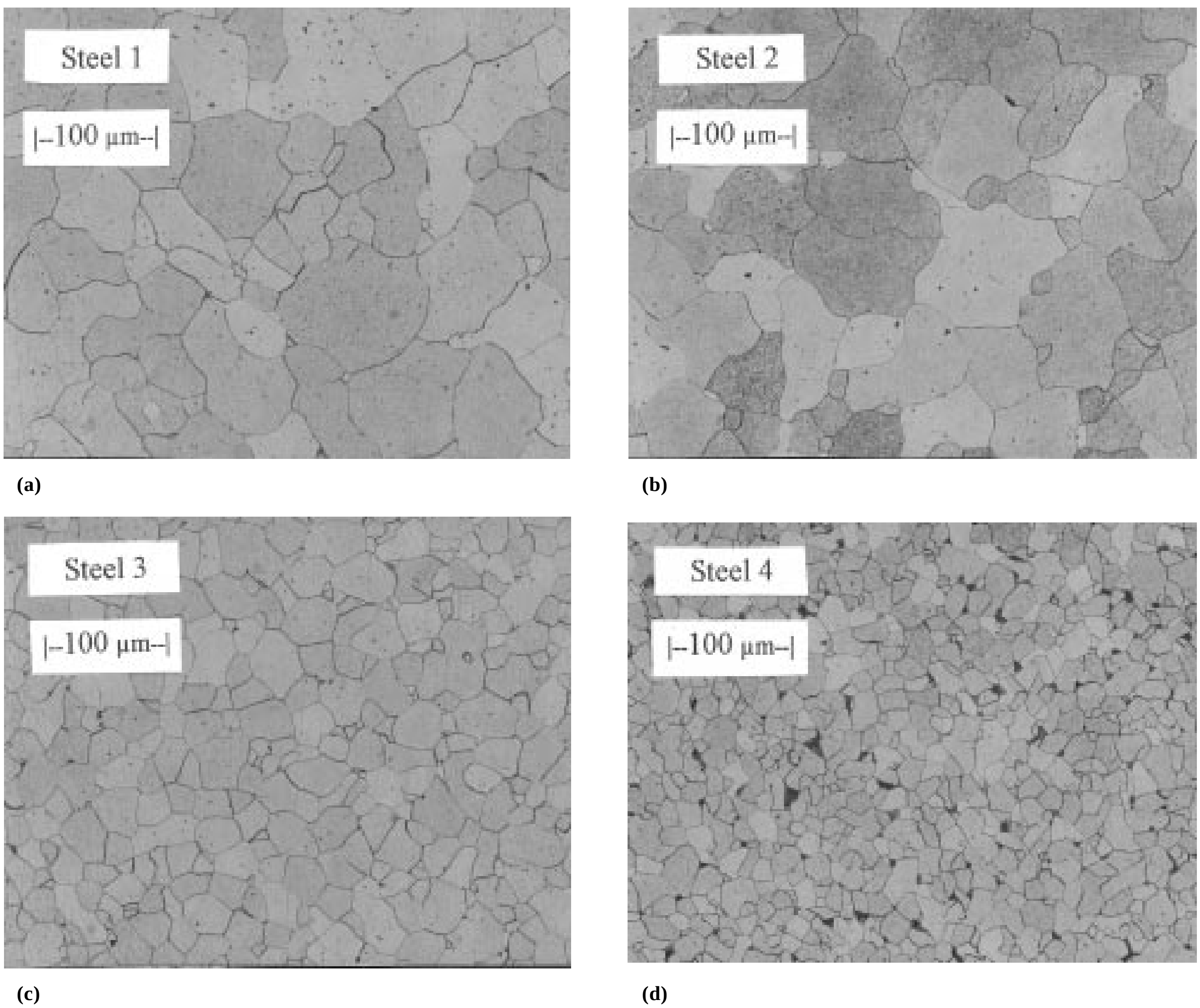

Fig. 2 Transverse nital-etched sections in 16 mm diameter hot-rolled steel wire rod showing grain sizes ASTM 5½ in steels 1 and 2, ASTM 7 in steel 3, and ASTM 9 in steel 4 with an original magnification of 200×

strength decreased 3.3 N/mm^2, and tensile strength decreased 2.4 N/mm^2 for each added 10 ppm B. The influence of boron on microstructure and mechanical properties in mild steels is thoroughly reported in Ref 8 and 9.

2.2 Testing Procedure

Charpy V-impact test specimens were manufactured from hot-rolled 16 mm diameter wire rod according to standard EN 10 045-1 for pendulum impact testing. The ferrite grain sizes were determined from nital-etched transverse sections and classified according to the ASTM scale (Fig. 2). Table 2 gives the corresponding mechanical properties of the hot-rolled wire rod. Any perceptible longitudinally orientated grain shape anisotropy was detected in the investigated steels.

The test temperatures were chosen to cover the entire transition temperature range, and the impact energy was verified by three tests at each test temperature. The ductile and brittle shapes of the fracture surface appearances were determined by comparison with a standard fracture series.

Figures 4 to 7 show the obtained impact energy values, supplemented with temperature dependence curves of fracture surface appearance determined from broken specimens. The transition temperature has been defined at an energy level

Table 2 Ferrite grain size and mechanical properties in the investigated steels

Steel No.	ASTM grain size	R_{eL}, N/mm^2	R_m, N/mm^2	R_{eL}/R_m	Z,%
1	5½	172	304	0.57	82.4
2	5½	183	306	0.60	78.9
3	7	205	319	0.64	78.2
4	9	262	369	0.71	72.9

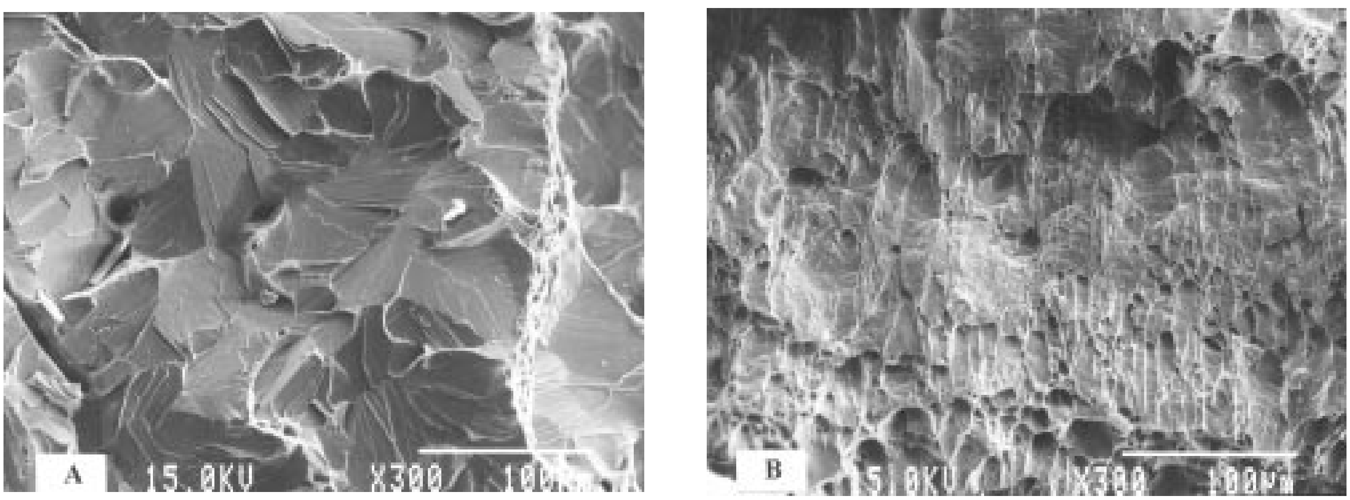

Fig. 3 Change in brittle-to-ductile fracture appearance in steel 2 in specimens tested at (a) +20 °C and (b) +45 °C

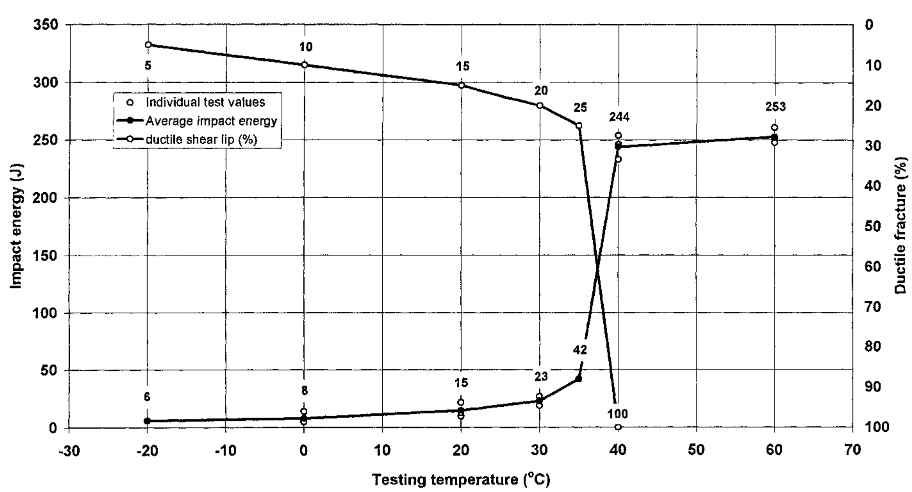

Fig. 4 Charpy V-impact energy versus temperature in steel 1

corresponding to 50% (FATT). The fracture surfaces in specimens representing the upper and lower shelves in the energy curves were studied by scanning electron microscopy, accordingly.

3. Discussion

The upper-shelf energies, ductile-to-brittle transition temperatures, and spread of energy results with respect to α-grain

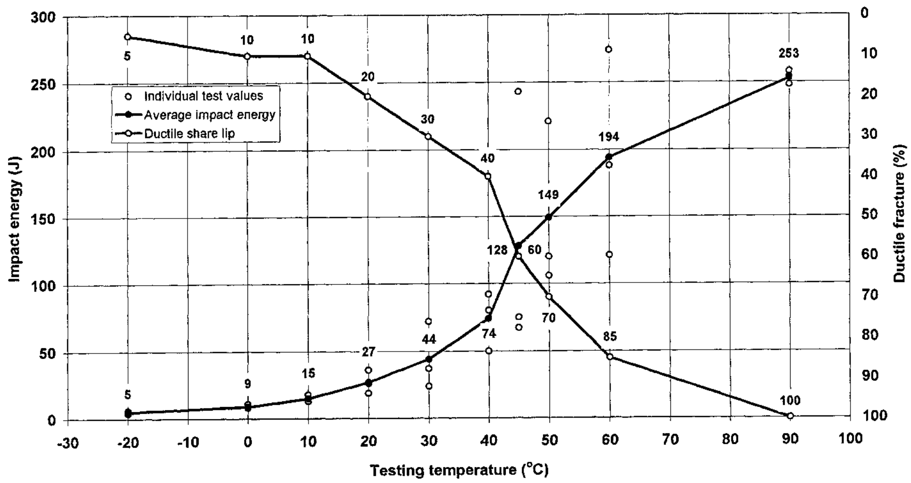

Fig. 5 Charpy V-impact energy versus temperature in steel 2

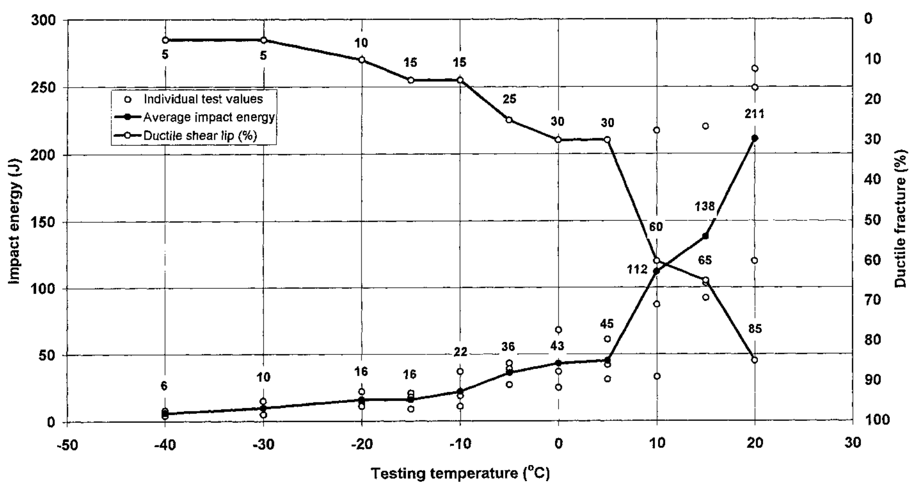

Fig. 6 Charpy V-impact energy versus temperature in steel 3

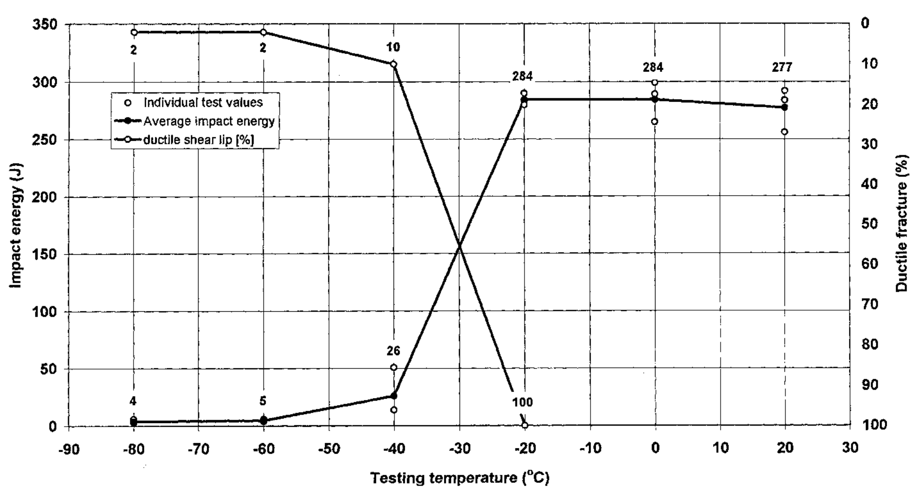

Fig. 7 Charpy V-impact energy versus temperature in steel 4

size and mechanical properties were used as criteria for assessment of the steels in the study. Transition temperatures between –29 and +50 °C, as well as upper shelf energies between 249 and 282 J, were obtained with respect to the investigation procedure. The Charpy-V impact energy characteristics of each steel have been summarized in Table 3.

Because the influence of temperature on yield strength is more efficient than it is on tensile strength, it is meaningful to assess the relationship between the measured mechanical properties on the impact energies expressly at room temperature. Thus, the impact energies in all steels at +20 °C cannot immediately be considered in relation to R_{eL} and R_m because the appearance is clearly brittle in steels 1 and 2 and apparently tough in steels 3 and 4.

Steels 1 and 2 are exceedingly similar regarding chemical composition and tensile strength, whereas a slight difference has been measured in yield strength, R_{eL} (11 N/mm^2), and reduction of area at fracture, Z (3.5%). The appearances of the transition curves in steels 1 and 2 show some disparities regarding transition temperature range and dispersion among individual values. In steel 1 the transition is more steep and sharply defined during a narrow temperature range, coinciding with a small spread of results between individual measurements. Thus, much the same upper shelf energy levels (253 J) have been ascertained in both steels.

For the same analysis, tensile strength and grain size, a lower yield strength was presumed to derive lower impact energy values. However, because the toughness depends on the relationship between yield and fracture strength, the obtained impact energies in steels 1 and 2 were fairly consistent in relationship to the mechanical properties in the wire rod. At 20 °C the average absorbed impact energies (15/27 J), clearly below the transition regions by this means, corresponded with the R_{eL}/R_m ratios in the wire rod. Generally, any distinct connection can be stated between impact energy at 50% FATT and the transition temperatures. The difference in transition temperature (12 °C) between steels 1 and 2 can be contributed to unaffected fluctuations within the method.

The transition temperature of steel 3 (+16 °C) was nearly 30 °C lower compared with steels 1 and 2 due to less by a half-percent of boron and as a consequence of the resulting amendment in α-grain size. The variation between single measurements was outstanding at the upper test temperature range (>10 °C). The lower shelf curve shows two energy levels with a change from approximately 5 to 15 J to about 35 to 45 J at –10 °C. The transition temperature raises with circa 0.5 °C for each added ppm boron, based on the mean transition temperature (44 °C) and mean boron content in steels 1 and 2 versus the transition temperature and percent of boron in steel 3. The investigated upper temperature range was inadequate for confirming the 100% shear energy in steel 3 at temperatures above 20 °C.

Because carbon should decrease the upper-shelf fracture energies, the highest energy level for fibrous fracture was measured in steel 4 with 0.057% C. It can be observed that upper-shelf energy is assumed to be considerably higher in steels 1 and 2 without boron additions and thus reduced α-grain size.

Table 3 Impact energy characteristics for the investigated steels

Steel	Upper shelf energy, J	Temperature for 50% FATT, °C	Impact energy at 50% FATT, J
1	249	+38	175
2	253	+50	150
3	(211)(a)	+16	150
4	282	–29	175

(a) Insufficient temperature range for assessment of 100% shear energy

4. Conclusions

The objective of this study was to determine the ductile-brittle transition behavior in four hot-rolled, low-carbon steels with a particular emphasis on the influence of boron. The following conclusions can be drawn:

- Transition temperatures between –29 and +50 °C based on 50% FATT explicated by the material properties were obtained. The upper-shelf energies alternated between 249 and 282 J.
- The transition temperature rose with circa 0.5 °C for each added ppm boron at least as a consequence of an enlargement of the ferrite grain size.
- The maximum highest upper-shelf energy and lowest transition temperature can be observed in the steel without boron additions containing the highest contents of carbon, silicon, and manganese.

Acknowledgments

This study was completed at the Fundia Dalsbruk steel wire rod rolling mill in Finland. The author wishes to express his gratitude to the staff at Rautaruukki Steel research center and the staff at Fundia Dalsbruk wire rod mill for the contribution in connection with the material investigation.

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