Mechanical Properties of Spring Steels at Room and Low Temperatures

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Abstract

Three spring steels were compared in their mechanical properties at room and low temperatures. The materials, the Cr-V, Si-Cr and Ni-Cr-Mo steels investigated in two different temper conditions, were subjected to tensile tests and to fracture toughness determination at temperatures ranging from + 20° C to -40° C. The fatigue limit at room temperature and the transition temperature curves through Charpy impact tests were also determined.

The importance of considering the variability of the mechanical properties as a function of temperature for the design of components supposed to be exercised in low-temperature environments is emphasized.

Riassunto

Sono state confrontate le proprietà meccaniche di tre acciai per molle legati al Cr-V, Si-Cr e Ni-Cr-Mo. I materiali, studiati in due diverse condizioni di rinvenimento, sono stati sottoposti a prove di trazione e di tenacità alla frattura a diverse temperature nell'intervallo da +20°C a -40°C. Il quadro delle analisi è stato inoltre completato mediante prove di fatica e con la determinazione delle curve di di transizione duttile-fragile.

I risultati hanno enfatizzato l'importanza di tenere in debita considerazione la variazione delle proprietà meccaniche in funzione della temperatura in fase di progetto di componenti operanti anche a basse temperature.

Key Words:

spring steels, Cr-V steel, Si-Cr steel, Ni-Cr-Mo steel, low-temperature mechanical properties, Charpy impact properties, tensile properties, fatigue, fracture toughness.

Introduction

The transport industry requires large-scale application of elastic components which must be manufactured with special steel grades, specifically developed to improve their elastic properties. Recent trend toward energy saving, reduction of costs and improvement of performances has led to the exploiting of the material strength up to its maximum level even in safety components which are exercised in a wide range of temperatures and loading conditions.

In literature there is a limited number of papers dealing with spring steels [1], especially those considering their basic mechanical properties as a function of the temperature at sub-zero levels. These data are indeed of great importance for the design of spring components that must sustain in service repeated loads without deforming plastically or fail in a brittle manner. Impact resistance for accidental high-rate overloading and fracture toughness properties are also demanded to assure safety and reliability to elastic components in the transport industry.

The standards of several European and American countries [2-6] dealing with spring steels, listing the main features of these alloys do not concern about their properties at levels below room temperature. However, the existing regulation for design of safety components, particularly for the wire transportation, is moving toward an increased sensitivity to this problem and at least the minimum impact toughness at temperatures ranging from 0º C to - 40º C, depending on the safety level of the component and on the regulation, are being stated.

High strength and ultra-high strength spring steels currently adopted feature tailored chemistry and thermal treatments specifically developed to raise the yield strength and the fatigue resistance while maintaining the toughness and impact resistance of the material at satisfactory levels. Other characteristics such as the resistance to relaxation under load [7,8], the tendency to surface decarburization and hardenability are also of interest and drive the designers through the choice of the steel. Amongst these, the Cr-V, the Si-Cr and the Ni-Cr-Mo grades examined in this paper are of great interest for their properties, albeit very different in their chemistry.

The Cr-V steels feature high strength, fine structure and grain growth resistance mainly related to the presence of vanadium, together with resistance to surface decarburization. Moreover, these alloys can be further strengthened for specific applications through the precipitation of vanadium carbides (secondary hardening) provided the steel is austenitized at temperatures above 1100° C and tempered at temperatures higher than 550° C.

The Si-Cr steels, still keeping their strength to considerably high values, are widely used also due to their lower cost. The presence of a high amount of silicon brings about an excellent resistance to the tempering of the martensite and to the relaxation under load (sag resistance) owing to the refinement of the tempered carbides [1,7].

Finally, Ni-Cr-Mo steels are mainly employed for their high toughness properties, it being possible to temper them to high hardness levels maintaining a significant ductility [9]. The hardenability of these steel grades is excellent despite the decreased carbon content, while the fatigue resistance is somewhat lower with respect to the above mentioned spring steels. The Ni-Cr-Mo steels are normally not widely used by European spring producer and are even neglected in the DIN [4] and UNI [6] standards for spring steels. On the contrary, there is an extensive application of such steel grades in the U.S.A.

Materials and Heat Treatments

Three different spring steels were investigated, namely the UNI-50CrV4, the UNI-60SiCr8 and the UNI-39NiCrMo3 alloys according to the codes given by the Italian standard which roughly correspond to type 6150 H, 9262 H and 4140 AISI steels, respectively. The materials were supplied by the producer in the form of hot-rolled bars with diameters ranging from 27 to 36 mm. The chemical compositions of the steels are listed in Table 1.

TABLE 1 - Chemical composition (wt.%) of the materials investigated.

	C	Si	Mn	Cr	Ni	Mo	V	S	P	Cu
50CrV4	0,48	0,30	0,91	0,95	0,20	0,05	0,14	0,008	0,016	0,28
60SiCr8	0,57	1,82	0,87	0,25	0,18	0,04	-----	0,007	0,009	0,12
39NiCrMo3	0,40	0,26	0,78	0,83	0,98	0,22	-----	0,008	0,021	0,02

To investigate the material properties, two heat treatments were considered, chosen amongst those most widely used by spring producers: a low-hardness temper (L) corresponding to values of 39-41 HRC, and a higher-hardness temper (H) corresponding to 44-46 HRC. The austenitizing treatment was carried out at a temperature of 880° C for all the three steels for 30 minutes followed by quenching in oil at 80° C. The tempering treatment was then performed for l hour at the temperatures given in Table 2.

TABLE 2 - Tempering temperatures of the materials investigated

	Temperature (°C)	
	H	L
50CrV4	465	540
60SiCr8	500	575
39NiCrMo3	440	530

Experimental

With the aim of studying the room- and low-temperature behaviour of the considered spring steels, temperatures varying from +20° C to - 40° C were chosen for the tensile and fracture toughness tests. This range agrees with the design regulations mentioned above, the lower temperature being representative of extreme condition employment for transportation applications.

The received hot rolled bars were first rough machined to the diameters required for specimen fabrication, heat treated and then ground to size. Samples taken after the heat treatment were subjected to standard metallographic examinations to check the structure and the inclusion content of the steels. The materials were of uniform tempered martensitic structure, as expected considering the presence of the alloying elements and the limited diameters or thicknesses of the specimens. The inclusions, detected on longitudinal sections of the bars, were in extremely low quantity mainly of manganese sulfide type with elongated shape. The inclusion level and the microstructure were certainly comparable for the three steels under investigation.

Charpy V-notch impact tests were performed to obtain the transition temperature curves according to the ASTM 23-88 standard at temperatures ranging from -60° C to +120° C.

The tensile tests were carried out at room temperature and at 0° C, -20° C, and -40° C with a Instrom 1195 (maximum load 100 KN) equipment. A constant crosshead speed of 0.5 mm/min was chosen for the tests which corresponds to an initial strain rate of 3.3 10^{-4} s^{-1}. Round section specimens were used with a gauge length of 40 mm and a diameter of 8 mm. The low temperature tests were performed bv straining the specimens placed in a thermostated liquid.

The fracture toughness determination was performed by applying the linear elastic fracture mechanics method (ASTM E 399-90 standard) or, where not acceptable due to the specimen dimensions, the J-integral approach (ASTM E813-89 standard). The three point bend specimens had the dimensions: B = 11 mm, W = 22 mm, S = 85 mm. These tests were carried out either at room temperature or at -40° C.

For the rotating bend fatigue tests, hourglass shaped specimens (minimum diameter: 6 mm) were used. The fatigue limit, defined at 2.8 10^6 cycles, was statistically determined according to the staircase method. The samples were tested at a frequency of about 1200 cycles min^{-1}. All the specimens were given a surface finish of R_A = 0.02 - 0.05 µm on the shaped length, measured by checking a gauge length of 1. 7 mm in the minimum-diameter region of the specimen.

Results and Discussion

CHARPY IMPACT TOUGHNESS. The problem of brittle behaviour in spring steels is of great concern and can be accounted for by three main factors which may act simultaneously. Spring steels are usually tempered to high hardness to reach elevated strength levels but this also brings about low toughness properties; the tempering temperature might lie in the embrittling interval and lastly, the metals can be loaded in low-temperature environments. The charpy impact test was chosen to evaluate the susceptibility of the steel to brittle behaviour and to supply a rough evaluation of the material toughness through an experimental test commonly reproducible by industrial laboratories. Even if a clear picture of the mentioned effects and their interactions is not easily imaginable, these tests were supposed to show the general trend and to supply comparisons as a function of the testing temperature and the tempering level.

The V-notch impact transition-temperature curves of the materials investigated are depicted in Fig. 1.

The transition temperatures of the steels in the L condition are about 75° C, >120° C and 18° C for the 50CrV4 the 60SiCr8 and the 39NiCrMo3 steels, respectively. On the contrary, the H temper materials do not show a marked transition to ductile fracture even at the highest temperatures. Their fracture mode can be considered as a low-energy rupture. The comparison of the different steels as a function of the hardness levels emphasizes the similarity of the behaviour of the 50CrV4 and the 60SiCr8 steels at least at room and low temperatures: the impact energies at 20° C are 18 J and 14 J for the L temper and for the H temper, respectively while at -40° C these become 13 J and 10 J. Not surprisingly, the Ni-Cr-Mo steel features higher absorbed impact energies. Particularly, the L temper material reaches 50 J at room temperature and still maintains 28 J at -40° C.

From the figures above discussed it is clear that in the temperature range of interest, five out of the six materials lies in their brittle-behaviour zone. However, it is worth noting that the transition curves strictly refer to specimens with a well defined geometry and notch root radius (R = 0.25 mm) loaded under specified condition. The curves might therefore be shifted to the left by lowering the loading rate or the triaxiality of the state of stress or might be shifted rightward by increasing the notch sharpness.

TENSILE PROPERTIES. The tensile data at room temperature are summarized in Table 3, whereas their dependence on temperature is depicted through the Figs. 2 to 7.

TABLE 3 - Tensile properties at room temperature of the materials investigated. UTS: ultimate tensile strength, YS: 0.2% yield strength, εpf: plastic strain at fracture, εpu uniform plastic strain, R. A. reduction of area, n: strain-hardening exponent, Energy: true strain energy at fracture.

		UTS (MPa)	YS (MPa)	YS/UTS	εpf (%)	εpu (%)	R.A. (%)	n	Energy (MPa)
50CrV4	H	1545	1445	0,94	8,2	3,6	26,5	0,066	85
	L	1365	1290	0,94	9,2	3,8	30,3	0,056	85
60SiCr8	H	1500	1370	0,91	8,7	5,1	27,5	0,081	108
	L	1350	1200	0,89	13,1	7,0	31,4	0,083	-
39NiCrMo3	H	1520	1395	0,92	9,9	1,1	47,0	0,081	94
	L	1255	1180	0,94	14,3	3,9	52,9	0,058	114

It has been generally stated that the tensile properties of a steel, particularly its ultimate tensile strength (UTS), are related to the hardness reached after the heat treatment. The three H-temper steels (Fig. 2a) confirm this tendency attaining, at +20° C and for the same hardness of 45 HRC, UTS ranging from 1500 and 1550 MPa while the average UTS values vary from about 1525 MPa at +20° C to 1620 MPa at -40° C. On the contrary, the constancy of UTS with hardness is not strictly verified for the L-temper steels (Fig. 2b) being the value attained by the 39NiCrMo3 grade at +20° C about a hundred MPa lower than those reached by the two other steels at the same hardness. This gap is also maintained at lower temperatures. As far as the yield strength (YS) and the YS/UTS ratio are concerned, it is observed that the Cr-V steel has in both the temper conditions the highest values. The Ni-Cr-Mo steel, notwithstanding the low yield strength in the L-temper condition, maintains similar YS/UTS ratios. Finally, the expected dependence of the UTS and YS values on temperature was observed in both the H-temper and L-temper conditions.

The strain-hardening exponent of the steels investigated in both the temper conditions does not change considerably with the test temperature, Figs. 3a and b, apart from an apparent decrease with increasing temperature in the L-temper Si-Cr grade. No well defined dependence on the tempering condition was observed.

The ability of deformation after the maximum load is of importance when considered as a safety limit before the ultimate failure of the material. By comparing the strain to fracture, Figs. 4a and b, the reduction of area at fracture, Figs. 5a and b, and the plastic strain at maximum load, Figs. 6a and b, it is possible to assess the ability of the steel to deform locally. Besides, another parameter useful in this analysis is the strain energy at fracture absorbed in the plastic range, Figs.7a and b, usually correlated to the toughness of the material, and evaluated as the area under the true stress-true plastic strain curve. Independently from the temperature level, it could be generalized that the 5OCrV4 steel in both the H-temper and the L-temper conditions shows low uniform plastic strains (about 3% and 4% in the H-temper and L-temper state, respectively) together with limited reductions of area and strains to fracture (about 7% and 10% in the H-temper and L-temper state, respectively). The information about the limited capability of deforming is underlined by a low true strain energy at fracture, notwithstanding the elevated UTS. In the H-temper condition a minimum in the ductility of the material at about 0° C is evident. The 39NiCrMo3 steel behaves in a completely different way, having large strains to fracture (9% and 14% in the H and L tempers, respectively) and elevated reductions of area (about 47% and 53% in the H-temper and -L-temper conditions, respectively) while there is a limited uniform plastic contribution to the total deformation at room temperature (2% and 4% in the H-temper and L-temper conditions, respectively). The material ability in sustaining local deformations is confirmed by the high values of true strain energy at fracture attained by the Ni-Cr-Mo steel in both the tempers. The Si-Cr grade, despite the large strains to fracture, comparable to those of the 39NiCrMo3 steel, shows limited reductions of area, comparable to those of the 50CrV4 steel, and large uniform plastic strains at maximum load. Even if the true plastic strain energy of this alloy is the highest in the H-temper condition and is comparable to that of the L-tempered 39NiCrMo3 steel, it is plain that the material can sustain only a restricted local deformation prior to fail.

Moreover it is worth reporting that the Si-Cr grade revealed a great notch sensibility so that, despite a careful grinding of the specimen surfaces, the results were affected by a noticeable scatter.

FRACTURE TOUGHNESS. At this stage of the research only the toughness data at +20° C and at -40° C are available. The fracture toughness values are reported in Fig. 8 as a function of the temperature; the straight lines connecting the data points are only intended to guide the eye rather than represent any linear relationship.

When comparing the toughness of the materials at room temperature as a function of the hardness level it can be noted that the 50CrV4 steel supplies reasonably high toughness values in the L temper condition, 98 MPa $m^{+1/2}$, while there is a steep decrease moving to the H temper which displays only 67 MPa $m^{+1/2}$. In the two hardness levels the 60SiCr8 alloy does not result in any significant difference in toughness at 20° C; the two values of 85 MPa $m^{+1/2}$ and 84 MPa $m^{+1/2}$, for the H temper and the L temper respectively, are in any case lower than that of the 50CrV4 steel in the L temper. The 39NiCrMo3 steel is characterized by markedly high fracture toughness values; the H temper alloy lies at the same level of the 50CrV4 L while the L temper material reaches the value K_Q = 112 MPa $m^{+1/2}$

The drop in toughness due to the lowering of the testing temperature for the three H-temper materials is roughly of the same amount. On the contrary, the L-temper materials are affected by heterogeneous behaviours; the different toughness values of the Cr-V and of the Si-Cr grades at room temperature result in similar values at -40° C. This supports the hypothesis, which will be confirmed by further investigations, that the transition temperature of the 50CrV4 steel under the fracture toughness testing conditions lies in the considered temperature range while the 60SiCr8 steel shows at both temperatures a brittle behaviour. Of particular interest is the 39NiCrMo3 L alloy. This material maintains a marked ductility even at -40° C so that the J-integral approach was necessary to evaluate rigorously the toughness values. It is apparent from the two figures at +20° C and at -40° C, 0.181 MPa m and 0.174 MPa m respectively, that the steel behaves in any case in a ductile manner. The transition temperature curve of this metal is therefore shifted to the left due to the lower strain rate, despite the sharper notch with respect to the Charpy specimens.

FATIGUE RESISTANCE. The fatigue resistance values, along with their standard deviations for a life of 2.8 10^6 cycles are summarized in Table 4.

TABLE 4 - Fatigue limits and standard deviations of the materials investigated

		Mean Fatigue Limit (MPa)	Standard Deviation
50CrV4	H	752	14.9
	L	698	8.4
60SiCr8	H	746	18.4
	L	712	14.9
39NiCrMo3	H	677	10.5
	L	678	7.6

It is evident that the Cr-V and the Si-Cr steels behave very similarly in fatigue loading, both in the H-temper and in the L-temper conditions. The increase in hardness of 5 HRC has led to an improvement of the fatigue limit of 54 MPa for the 50CrV4 and of 34 MPa for the 60SiCr8 steel. The 39NiCrMo3 alloy shows lower fatigue resistance values both in the H temper and in the L temper. This feature can be accounted for by the lower elastic limit of this steel as compared to the others, not directly measured during the tensile tests but qualitatively noticed on the stress-strain plots. The ability to deform plastically of this steel is indeed favorable for its toughness but also gives rise to lower fatigue limits due to the ease of movements of the dislocations around the fatigue-crack nucleation sites. The increase in hardness from 40 to 45 HRC for the Ni-Cr-Mo steel does not alter significantly the fatigue limit.

The data scatter, strictly related to the standard deviation values, roughly reflects the toughness of the materials or in other words, the ability of the steel to blunt occasional surfacial microcracks. The 60SiCr8 alloy in both the tempers and the 50CrV4 H steel proved to be the most notch sensitive materials giving rise to the highest standard deviations.

Finally, it must be remembered that the fatigue data above discussed refer to polished specimens. It is well known that the fatigue properties of springs subjected to dynamic loading can be sensibly increased by carrying out shot peening surfacial treatments. For spring steels, the improvement brought by a properly performed shot peening process can be evaluated in a gain of about 40% of the fatigue limit [10]. Fatigue tests on shot peened springs manufactured with the materials studied are scheduled and the results will be published in the near future.

Conclusions

From the results of the present investigation the following conclusions can be drawn:

The transition temperatures of the steels, determined by Charpy impact testing are: 75° C, >120° C and 18° C for the 50CrV4, the 60SiCr8 and the 39NiCrMo3 steels in the low-hardness temper (40 HRC), respectively whereas the higher hardness temper materials (45 HRC) do not show a marked transition to ductile fracture even at the highest temperatures covered during the tests.

The materials belonging to the same temper condition (i.e. hardness level) attain the same strength values, Table 3, apart from the 39NiCrMo3 L steel whose UTS is about 100 MPa lower with respect to the other L-tempered alloys. The 50CrV4 steel features the lowest ductility, the Si-Cr and the Ni-Cr-Mo grades having the same strain to fracture but differing in their necking contribution. As expected, the increase in strength with the decrease of the temperature is observed while the ductility and the workhardening behaviour do not change significantly.

The fracture toughness values of the materials are reported in Fig. 8. The decrease in toughness with the decrease of the temperature for the three H-tempered materials is nearly constant. A different behaviour can be seen for the L-tempered steels: by lowering the temperature from +20° C to -40° C the Cr-V grade displays the greatest drop in toughness (from 98 MPa $m^{+1/2}$ to 66 MPa $m^{+1/2}$), the 60SiCr8 steel, with a lower room-temperature toughness, is subjected to a limited loss while the Ni-containing alloy maintains constant its high toughness.

The fatigue limits of the materials investigated are listed in Table 4. The two Cr-V and Si-Cr steels having the best fatigue resistance and the 39NiCrMo3 grade being insensitive to the hardness level in the considered interval.

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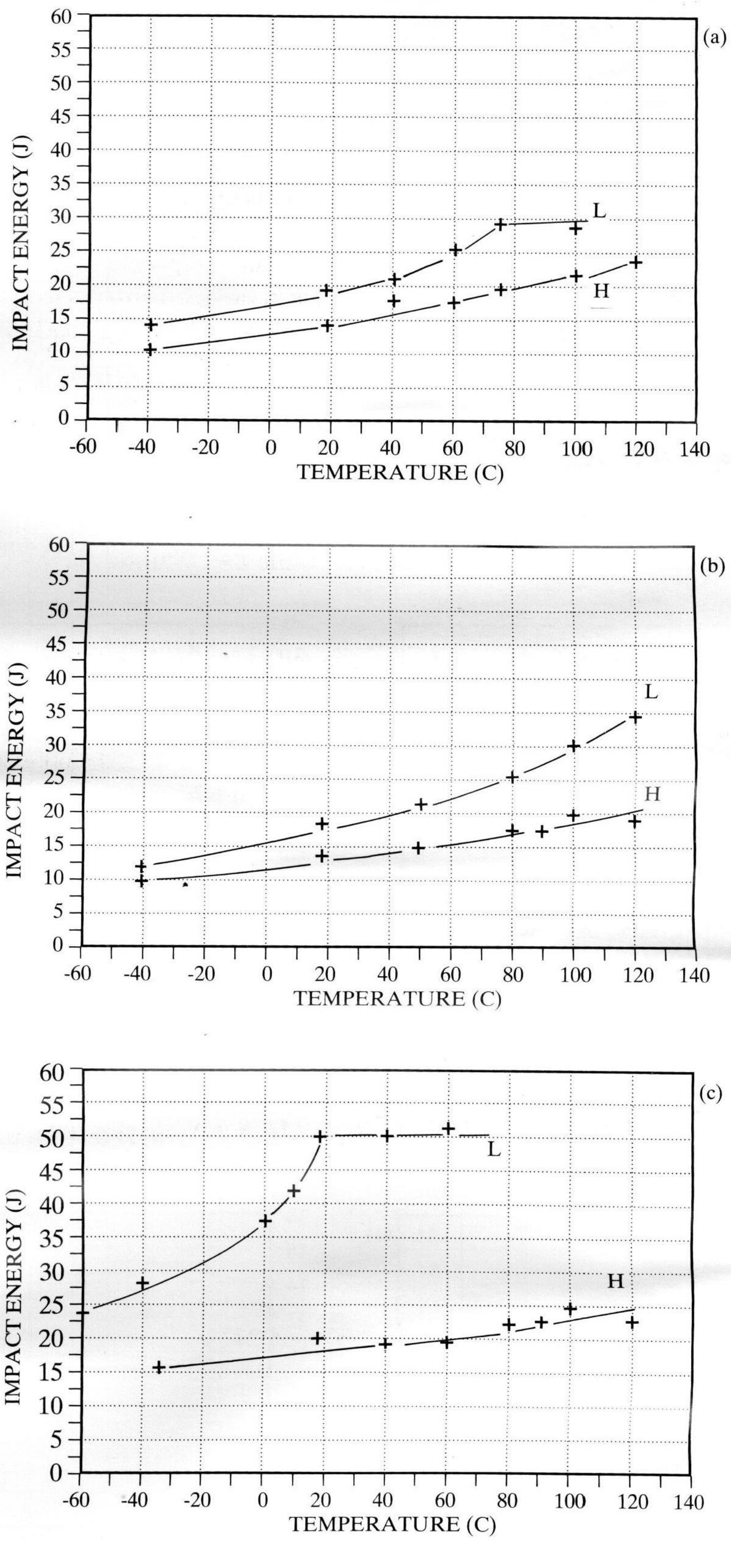

Fig. 1
Transition-temperature curves of the materials investigated.
a) 50CrV4, b) 60SiCr8, c) 39NiCrMo3.

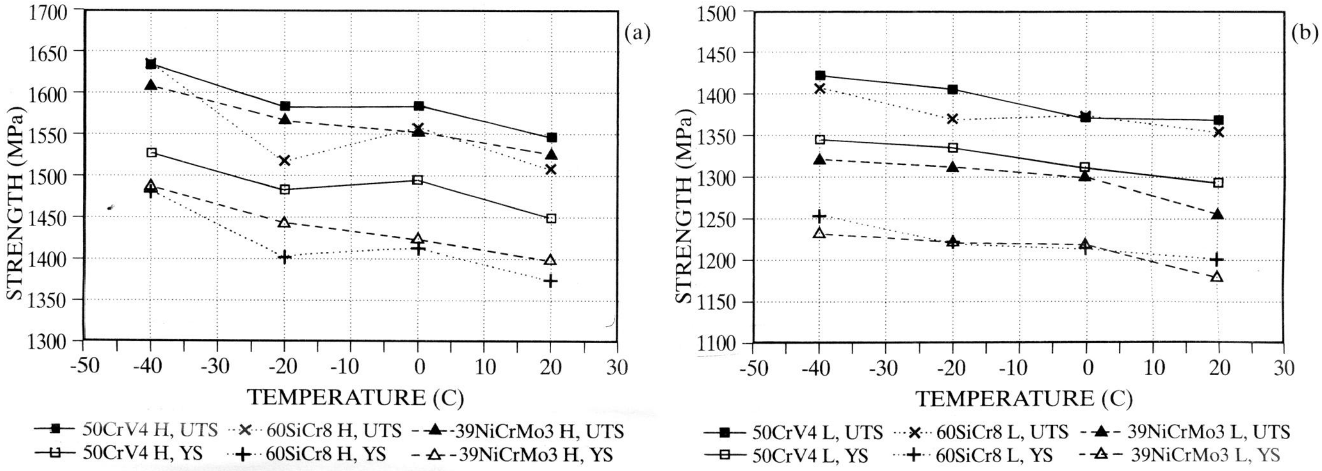

Fig. 2

Ultime tensile strenght and yeld strenght of the materials investigated. a) H temper, b) L temper.

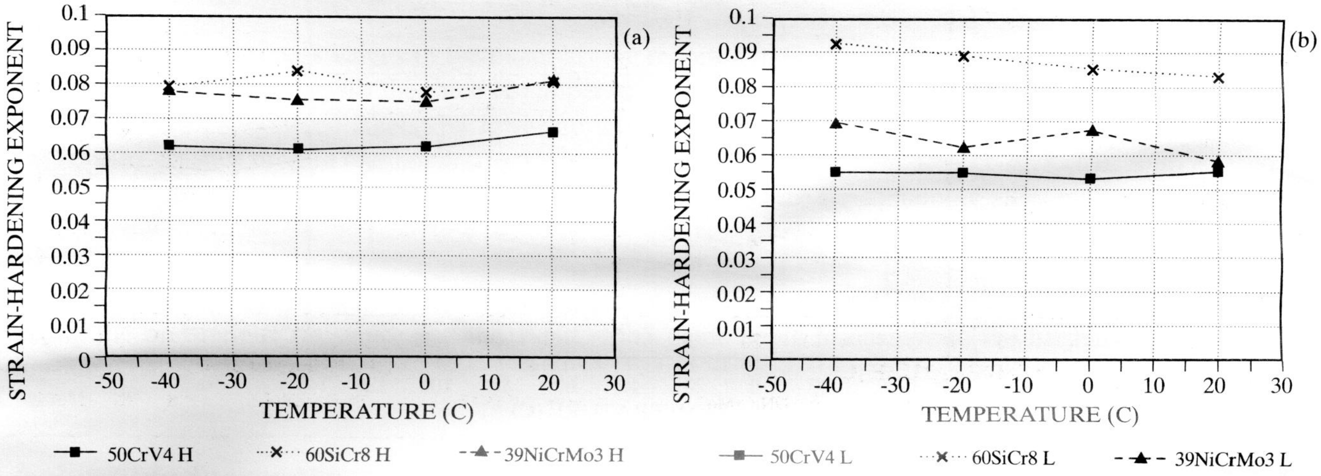

Fig. 3

Strain-hardening exponent of the materials investigated. a) H temper, b) L temper.

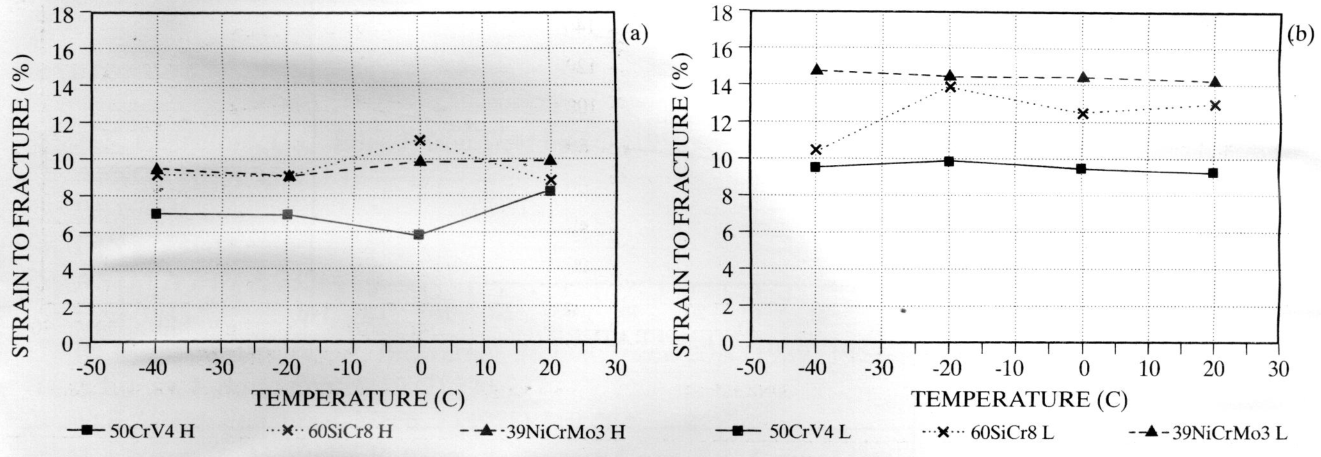

Fig. 4

Strain to fracture (εpf) of the materials investigated. a) H temper, b) L temper.

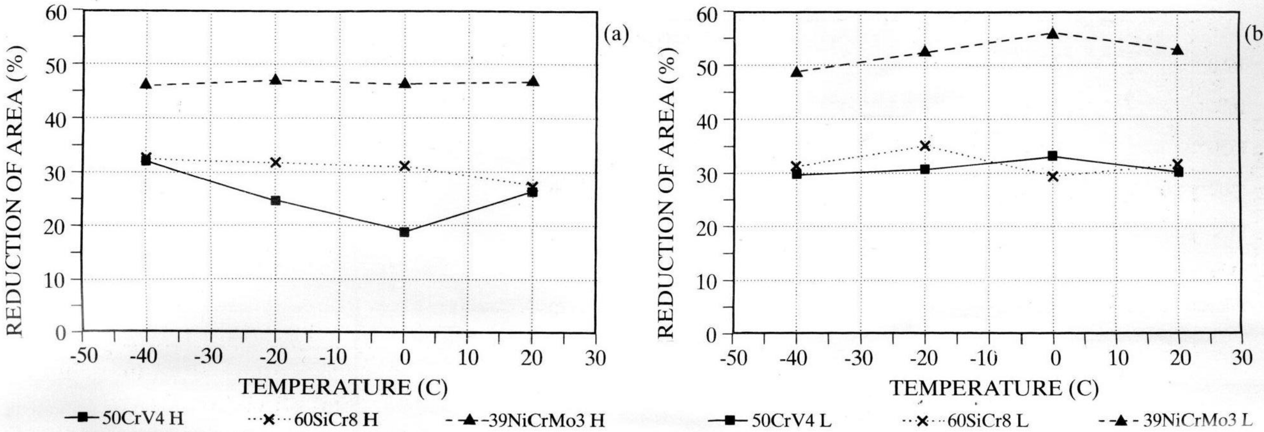

Fig. 5
Reduction of area at fracture of the materials investigated.
a) H temper, b) L temper.

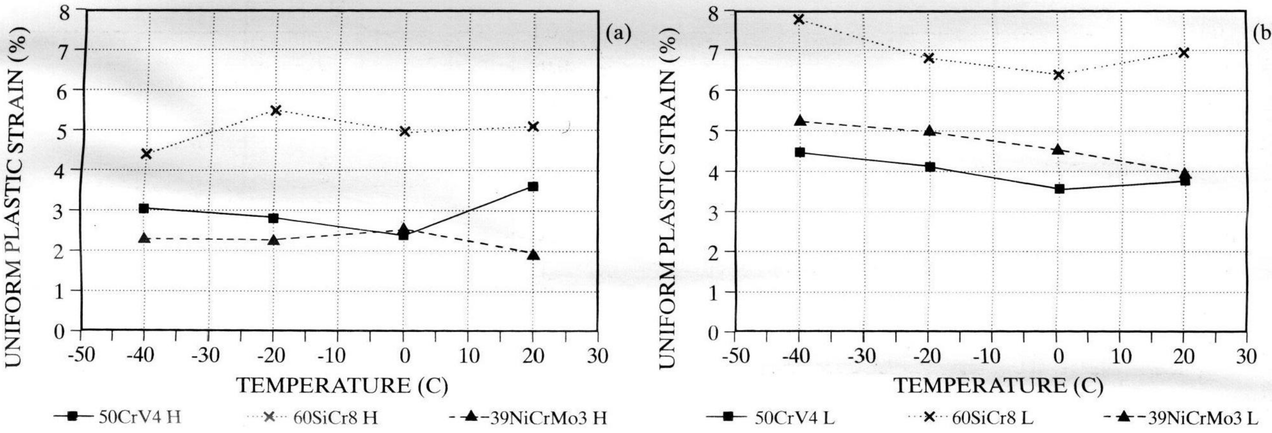

Fig. 6
Uniform plastic strain at maximum load (εpu) of the materials investigated.
a) H temper, b) L temper.

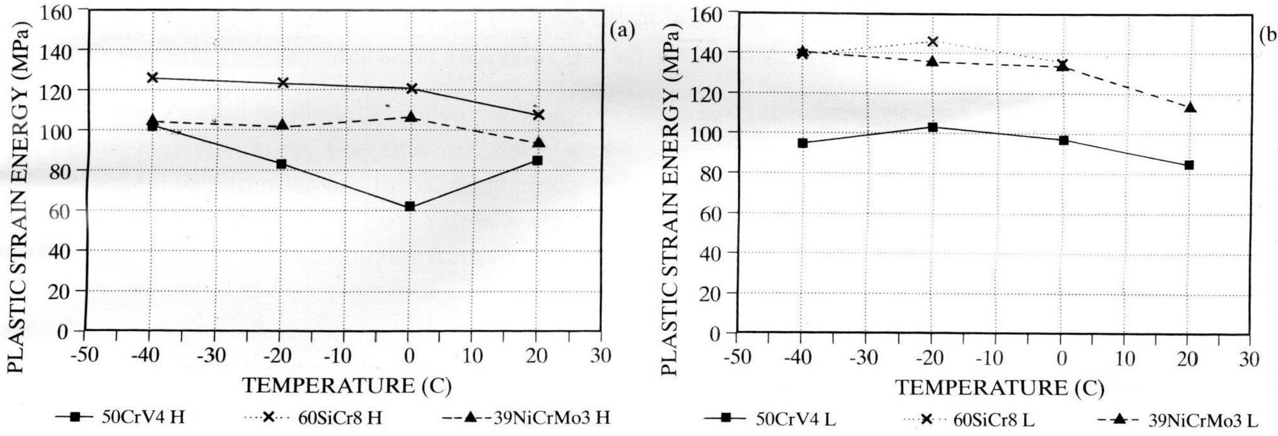

Fig. 7
Plastic strain energy at fracture of the materials investigated.
a) H temper, b) L temper.

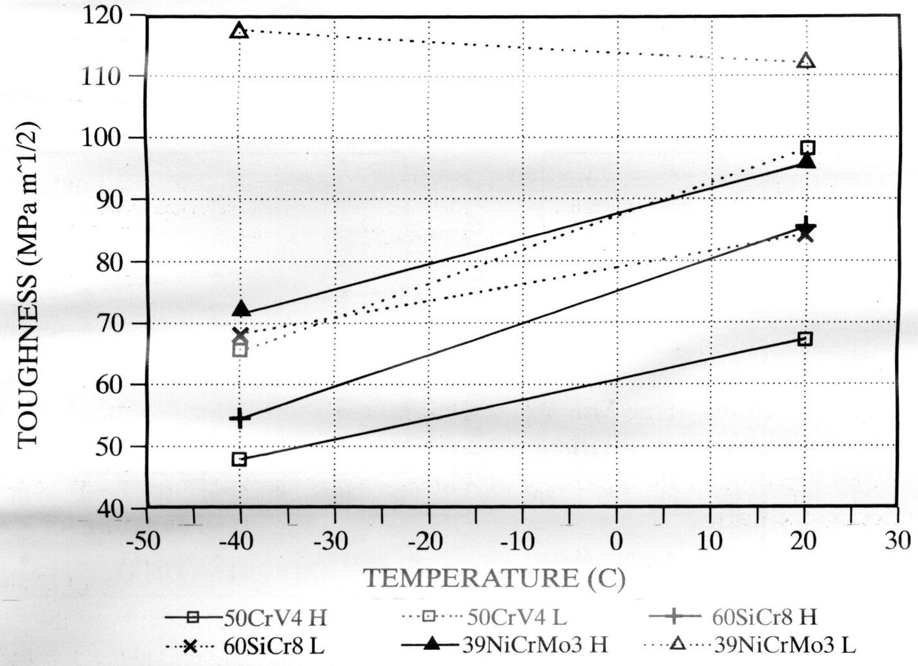

Fig. 8

Fracture toughness data (Kic in MPa $m^{+1/2}$) vs. temperature.
For the 39NiCrMo3 steels the KQ values are reported.