FRACTURE PROPERTIES OF THE SELECTED FERROUS MATERIALS USED IN POWER TRANSMISSION LINE HARDWARE

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ABSTRACT

The effects of loading rate and test temperature on the impact energies and fracture toughness have been investigated for some ferrous alloys used in the transmission line hardware components. Selected steels are 300 WT, 300 W, oil-quenched 1541 & 4130 and old & new Dywidag materials. Effects of mar-quenching and the forging on the fracture properties of the 1541 steels were quantified.

KEYWORDS

Quasi-static fracture toughness (K_Q, K_{max}), dynamic fracture toughness(K_{ID}), charpy impact energies, 50 % FATT, stress-strain data

INTRODUCTION

The traditional design practices employed to ensure the structural integrity of electrical power transmission line hardware are based on smooth body design concept. This concept ensures that the operating stresses in the components do not exceed the materials's yield strength. In most cases, the tender documents released to manufacturers of hardware components are solely based on a performance specification, which generally includes dimensional tolerances, minimum tensile strength, impact energy and workmanship. Failures of transmission line hardware components occur time to time due to improper heat treatment, metallurgical problems, corrosive conditions, operating temperature, overload and design fault. Some examples of failure, observed in Canada, are given in Table 1.

More specific and stringent specifications for particular line hardware components have been introduced as a direct results of post-failure analyses utilising metallurgical examination and fracture mechanics analyses. Analytical and experimental studies(1-3), initiated through the Canadian Electrical Association (CEA), are being carried out to examine the design philosophy for the line hardware components based on the fracture mechanics methods.

A list of typical steels employed for transmission line hardware in Canada is given in Table 2. A fracture mechanics data base is being generated through a CEA project(3) and this paper presents the fracture properties of some selected ferrous alloys, currently being used by the Canadian electrical utilities for the line hardware components. The effects of quenching process, fabrication method, loading rate and test temperature on fracture properties are discussed.

Table 1. Some case histories of Canadian transmission line hardware failure(6,7)

Components	Causes
Anchor assembly U-bolts	Strain-age-embrittlement (SAE)
Swing angle bracket	SAE
Splicing (plate) angle	SAE
Thrust links	SAE
Suspension assembly U-bolts	Fatigue
Shoulder eye balls	Improper heat treatment due to steel type contamination
Suspension shackles	Improper heat treatment
Lock washers	Hydrogen embrittlement
Guy Anchor rod	High transition temperature

Table 2. Ferrous materials utilized in transmission line hardware components in canada(3).

Component type	Un-heat treated	Q&T plain C or high Mn steels	Q&T low alloy steels
Yoke plates	CSA G40.21M 300 W,300 WT,350 WT, 400 W		
U-bolts & strain links	CSA G40.21M 300 W, 350 WT AISI 1018. 1035, 1541 ASTM A36	AISI 1038M, 1340, 1541	ASTM A320(L7C)
Forged hardware (including clevis & shackles)	CSA G40.21M 300 W,300 WT,350 W	AISI 1340,1541	AISI 4130, 4140
Anchor rods	CSA G40.21M 300 W,300 WT,400 W Dywidag (fully pearlitic steel) Commercial rebar (ASTM A615 gd 40/60)	AISI 1035	AISI 4130,4140, 4340 ASTM A320(L43)

MATERIALS

Plate materials (19 mm thick CSA G40.21 M 300 WT and 63 mm thick 300 W) were obtained from a hardware manufacturer. Anchor bars, made of CSA G40.21 M 300 WT (19 mm dia.) and old & new (GEWA)Dywidag materials (25 mm dia.), were received from the utilities and a supplier. Rolled and forged pieces of AISI 1541 steel (22 and 28 mm dia) and a rolled anchor bar made of AISI 4130 were obtained, in the fully annealed condition, from a manufacturer and a utility, respectively. The steel type, condition and chemical compositions are given in Table 3.

Table 3. Materials tested.

Alloy	Condition and heat treatment	Thick. or Dia. (mm)	Chemical Composition(wt %)								
			C	Mn	Si	Cr	Ni	S	P	Cu	Mo
CSA G40.21M											
300 WT	Plate	19	.16	1.36	.02	.02	.02	.005	.01	.03	<.01
300 W	Plate	63	.18	1.26	.26	.02	.01	.013	.019	<.01	<.01
300 WT	Rolled bar	19	.20	1.00	.24	.13	.13	.036	.020	.33	.01
AISI											
1541	Rolled bar,OQ	22	.44	1.55	.21	.15	.06	.018	.008	.11	.01
1541	Rolled bar,MQ	28	.42	1.51	.26	.05	.04	.015	.013	.10	<.01
1541	Forged bar,OQ	22	.44	1.54	.21	.15	.06	.016	.008	.11	.01
1541	Forged bar,OQ	28	.42	1.50	.26	.05	.04	.015	.014	.10	<.01
4130	Rolled bar,OQ	39	.31	0.93	.20	.94	.07	.02	.008	.19	.18
Dywidag material											
(old)	Rolled bar	25	.54	1.39	.70	.25	.41	.018	.013	.18	.01
(new)	Rolled bar	25	.15	0.67	.15	.06	.07	.018	.029	.08	<.01

Heat Treatment

All 1541 and 4130 steels were austenitized at 857° C. Some of the 22 & 28 mm dia. rolled and 22 mm dia. forged 1541 materials were quenched in an oil bath at 120° C and tempered at 621° C. The 28 mm dia rolled 1541 materials were mar quenched at 204° C for half an hour and subsequently air cooled and tempered at 621° C. The 4130 materials were quenched in fast oil at the room temperature and tempered at 565° C within half an hour of the quenching.

EXPERIMENTAL METHODS

Test Specimens

Location and orientation of test specimens, machined from the plates and the bars, are shown in Figure 1. The planes of fracture for the specimens, machined from the plates and bars, were in (T-L) and (L-R) direction, respectively.

A minimum of twelve full size (10 mm X 10 mm) charpy V-notched (CVN) specimens and four round/flat smooth tensile specimens were machined from each set of materials. Specimens were positioned at the centre (and at quarter for larger thickness or diameter) of the plate or bar material.

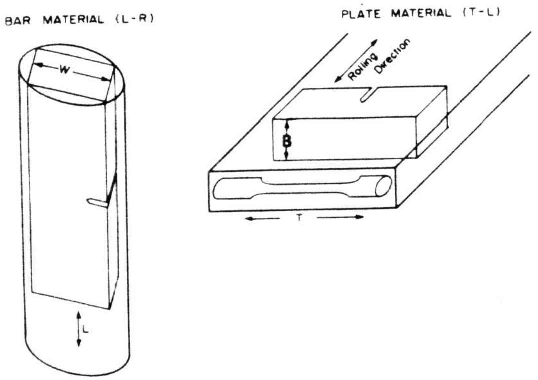

Fig. 1 Location and orientation of test specimens.

For the quasi-static fracture toughness tests, a minimum of four three-point bend specimens were machined either in (T-L) or (L-R) orientations for each set of materials. The width (W) and thickness (B) of the specimens varied from 15 mm to 44 mm and 10 to 44 mm, respectively. The dimension, B, of the bend specimens was kept as close as possible to the corresponding plate thickness or bar diameter. A minimum of four (10 mm X 10 mm) bend specimens were machined, from the centre of the each set of materials, for the dynamic fracture toughness test. All bend specimens (for quasi-static and dynamic toughness tests) were fatigue precracked according to the ASTM E399 test method(4).

Mechanical Testing

Full-size charpy specimens were tested at various temperatures, ranging from -90° C to 30° C, to establish the ductile-to-brittle transition behaviour of materials. Fifty percent shear fracture appearance transition temperatures (FATT) for the materials were determined. Minimum operating temperature for the transmission lines in Canada is about -45°C. Considering this fact, it was decided to carry out tensile tests at -45° C, in addition to the tests at room temperature i.e., 20° C. Yield strength, tensile strength and strain at fracture, at the above two temperatures, were obtained from the tensile tests.

Fracture Toughness Testing

Quasi-static fracture toughness tests were carried out according to the ASTM E 399 test procedure at 20° C and -45° C. Valid plane strain fracture toughness, K_{IC} or K_Q (based on the load at the 5 % secant offset), according to the standard was obtained for only a few of the steel types. But as the specimen thicknesses(B) were similar to the line hardware dimensions, the K_{max} values (based on the maximum load) obtained from all tests would relate to the fracture behaviour of the components. Therefore, the effects of various variables on the K_{max} values obtained from all quasi-static tests, are discussed in the next section.

Dynamic fracture toughness tests were carried out, at 20° C and -45° C, on pre-cracked V-notched (PCVN) specimens using an instrumented charpy impact test set-up. The dynamic fracture toughness (K_{ID}) values, corresponding to either the load at crack initiation or the equivalent load based on the equivalent energy method(5), were obtained from these tests.

RESULTS AND DISCUSSION

Tensile data

Some of the stress-strain data, obtained from the tensile tests, are shown in Figs. 2-4. Average yield stress and strain at fracture for the plate materials (300 WT & 300 W), at the room temperature, ranged from 360 to 372 MPa and 22 to 28%, respectively. Corresponding values at -45° C test temperature were 420 to 453 MPa and 24 to 31 % (Fig. 2). Average yield stress for the 300 WT bar material at the two test temperatures were 421 MPa and 481 MPa. The strains at fracture were in the range of 28 to 30%.

Stress-strain data for the rolled and forged 1541 oil-quenched materials are shown in Fig. 3. Average yield strength and strain at fracture were in the range of 880 to 940 MPa and 18 to 21%, respectively. For the rolled mar-quenched materials, average yield strength increased from 685 MPa to 733 MPa with the decrease in test temperature (Fig. 4). Yield strengths for the old & new Dywidag old & new materials and the 4130 materials at the room temperature were 431, 997 and 783 MPa, respectively.

Charpy Impact Data

The temperatures, corresponding to the fifty percent shear fracture of the broken V-notched charpy specimens, were -2° C and 20° C for the 19 mm thick 300 WT and 63 mm thick 300 W plate materials. The 50% FATT temperature for the 300 WT and 4130 anchor bar materials were 6 and -46° C, respectively.

Charpy Impact energies, normalised with respect to the remaining ligament area, are shown in Figure 5-7 for the 1541 and Dywidag materials at various test temperatures. Solid symbols represent the normalised impact energies obtained from the V-notched charpy specimen tests, whereas open symbols correspond to the pre-cracked V-notched (PCVN) specimen test. Temperatures, shown by arrows in the above figures, correspond to the 50% shear fractures for the materials. As expected, forging process improved the impact energies of the material (Fig. 5). Presence of a crack, in the forged and rolled oil-quenched 1541 materials, reduced the normalised impact energies obtained from the CVN specimen tests by almost 50% at the room temperature. The oil-quenched (OQ) 1541 material had a 50% FATT temperature of -20 ° C. Corresponding value for the mar-quenched (MQ) material was 7° C. Normalised impact energies obtained from the pre-cracked specimens of the mar-quenched and oil-quenched materials, tested at the room temperature, were 25% and 50% of their respective V-notched charpy energies (Fig. 6).

The old Dywidag materials had poor impact properties even at the room temperature(Fig. 7). The new (GEWA) Dywidag material had relatively good impact properties and had a transition temperature as low as -45° C. Normalised impact energies of the new Dywidag materials were reduced by 62% and 90% at 20° and -45° C test temperatures due to the severity of the notch.

Fracture Toughness Data

Valid plane strain quasi-static fracture toughness (K_Q) values ranging from 33 to 48 MPa√m at 20° C were obtained for the old Dywidag materials at 20° and -45° C. Moreover, tests conducted on the rolled mar-quenched 1541 and oil-quenched 4130 materials gave valid K_Q values of 83 MPa√m and 102 MPa√m respectively, at -45° C.

Effects of loading rate, test temperature and forging & quenching processes on the fracture toughness of the tested materials are shown in Figures 8-10. In all these figures, each point represents the average value of two test results. Solid and open symbols, shown in these figures, represent the average fracture toughness values (K_{max}, K_{ID}) obtained from the quasi-static and dynamic tests, respectively. The loading rate (dK/dt) for the quasi-static tests ranged from 0.49 to 3.35 MPa√m/s. Corresponding values for the dynamic tests were in the range of 10^5 to 10^6 MPa√m/s.

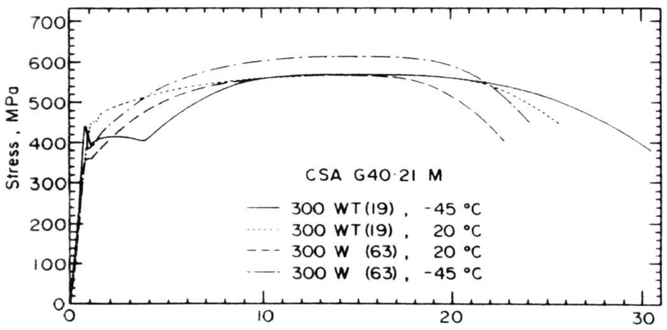

Fig. 2. Effects of test temperatures on the stress-strain data of the 300 WT and 300 W plate materials.

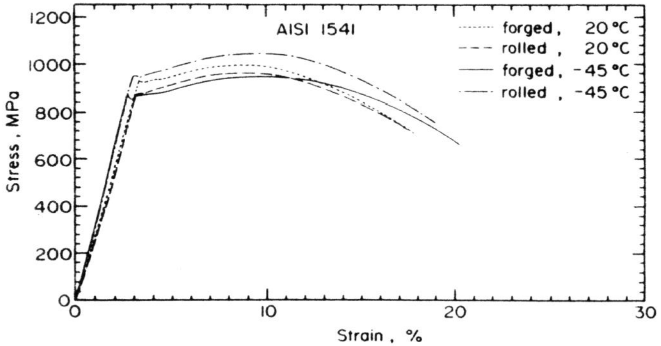

Fig. 3. Effects of forging on the stress-strain data of the oil-quenched 1541 materials.

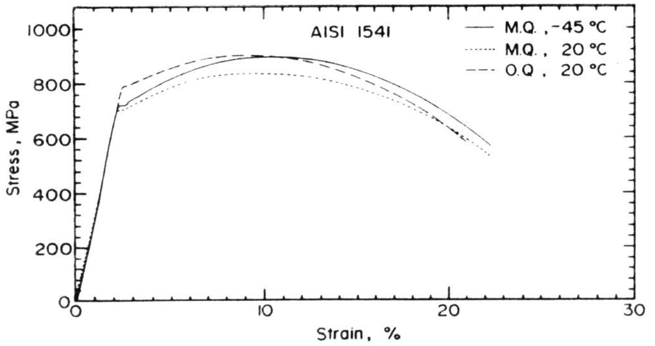

Fig. 4. Effects of quenching process on the stress-strain data for the 1541 materials.

Average values of K_{max} and K_{ID} for the 300 WT and 300 W plate materials are shown in Figure 8. No significant changes on the quasi-static and dynamic fracture toughness were observed at -45° C and 20° C test temperatures. The fracture toughness values, ranging from 73 to 86 MPa√m, were obtained from the quasi-static tests. With the increase in loading rate from 1 to 10^6 MPa√m/s, fracture toughness of the materials reduced to 41 - 47 MPa√m.

Effects of the forging of the 1541 oil-quenched materials on the static and dynamic fracture toughness are shown in Figure 9. Forging of the materials increased the fracture toughness by 6-8%, compared to the rolled materials. K_{max} values, ranging from 110 to 125 MPa√m, were obtained from the tests. At -45° C and 20° C test temperatures, K_{ID} values ranged from 49 to 56 MPa√m and 79 to 99 MPa√m, respectively for the rolled and forged materials.

Effects of quenching process on the fracture toughness of the rolled 1541 materials are shown in Figure 9. Straight oil quenched materials had superior fracture toughness, compared to the mar-quenched material. At -45° C test temperature, the fracture toughness of the oil-quenched material was approximately 20% higher than that of the mar-quenched material in the static and dynamic loading conditions. At room temperature, the dynamic fracture toughness of the oil-quenched material was almost two times that of the mar-quenched material. It should be noted that the results only apply to one set of commercial mar-quenched process variables.

K_{max} values of 48 to 58 MPa√m were obtained for the 300 WT anchor bar materials at the both test temperatures. Similar fracture toughness values were obtained in the dynamic condition. For the new Dywidag materials, static fracture toughness values were in a range of 77 to 95 MPa√m. No temperature effect was reflected on the K_{max} values. Whereas, the dynamic fracture toughness (K_{ID}) values were increased from approximately 43 MPa√m to 150 MPa√m with the increase in test temperature from -45° C to 20° C. The average static and dynamic fracture toughness for the 4130 steel were increased from 119 MPa√m to 132 MPa√m and 59 MPa√m to 85 MPa√m, respectively, with the increase in test temperatures.

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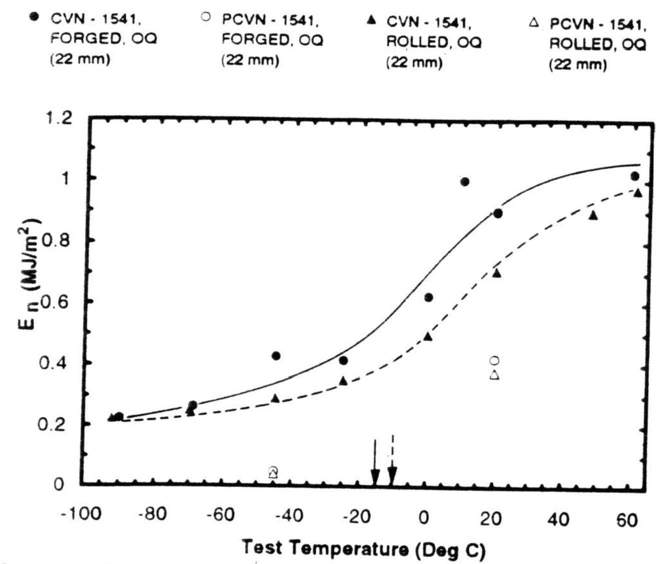

Fig. 5. Effects of forging and pre-existing crack on the normalised impact energies of oil-quenched 1541 materials.

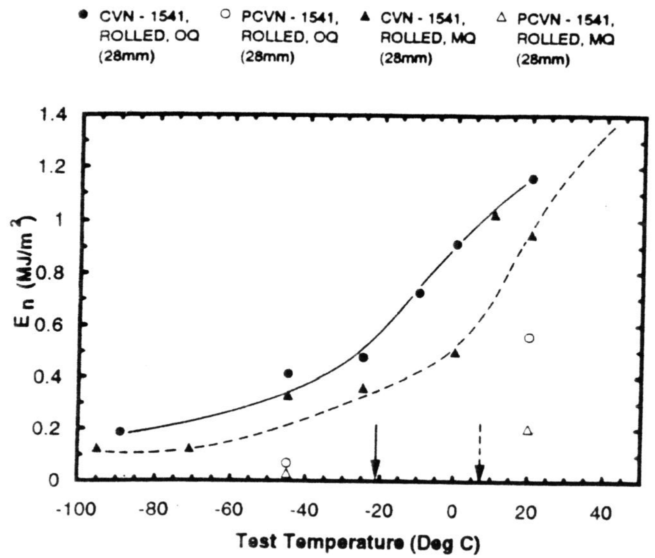

Fig. 6. Effects of quenching process and pre-existing crack on the normalised impact energies of the rolled 1541 materials.

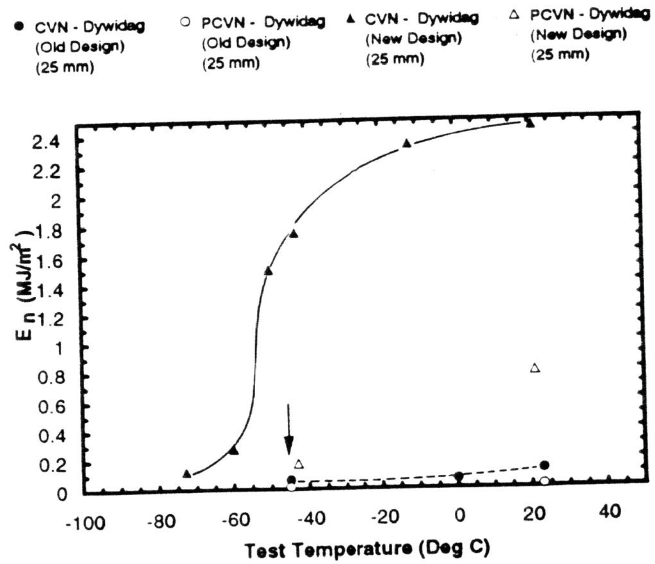

Fig. 7. Effects of pre-existing crack on the normalised impact energies of old and new Dywidag materials.

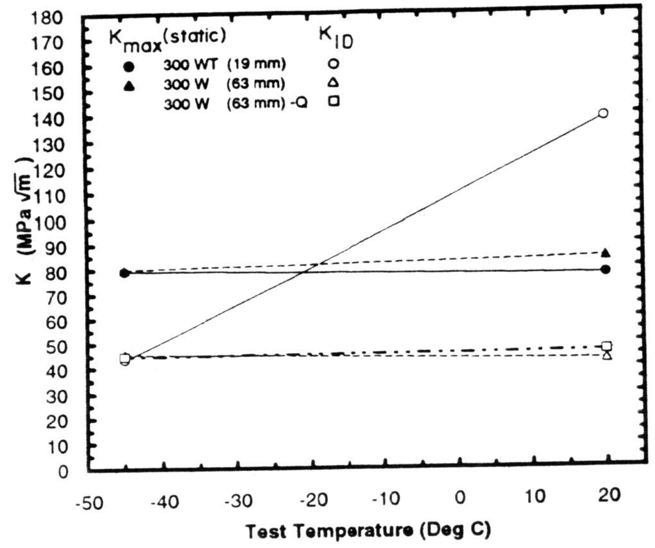

Fig. 8. Effects of the test temperatures and loading rate on the fracture toughness of the 300 WT and 300 W materials.

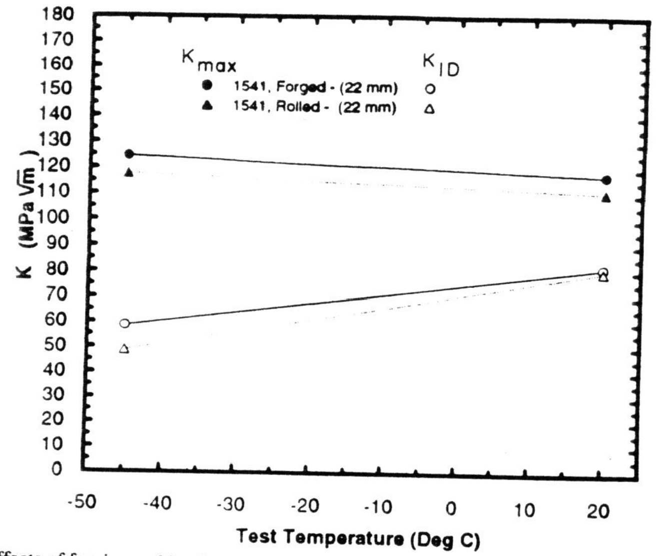

Fig. 9. Effects of forging and loading rate on the fracture toughness of the oil-quenched 1541 materials.

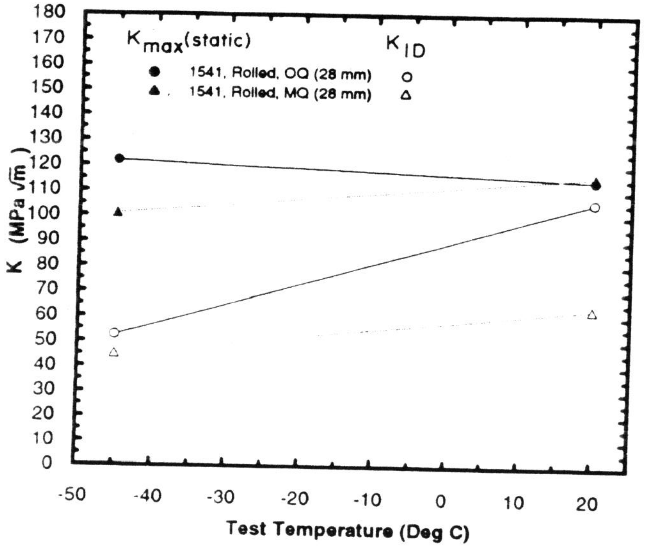

Fig. 10. Effects of quenching process on the fracture toughness of the rolled 1541 materials.