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STATIC AND DYNAMIC FRACTURE PROPERTIES OF HIGH STRENGTH STEEL CHAIN MATERIALS

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ABSTRACT

The development of future standards for high strength lifting chain will be based on performance, thus it is likely that toughness specifications will be included in these standards. Fracture mechanics makes it possible to define a minimum fracture toughness level for a component such that, in the presence of a defect, failure will not occur at the safe working load. The intention of this programme of research was to determine the fracture behaviour of conventional and boron-containing high strength steel chains over a range of operating temperatures and develop performance criteria for chain material to replace existing material specific requirements.

Charpy impact, quasi-static and dynamic fracture toughness tests were carried out on a conventional alloy chain material and two boron-containing chain materials, over the full operational temperature range of lifting chains. The differences between the materials were quantified in terms of ductile-brittle transition curve behaviour. The results clearly illustrated the superior behaviour of the alloy chain material with respect to the two boron-containing chain steels.

Engineering critical assessment methods were utilised to develop performance criteria for these lifting chain materials, allowing fracture stress data to be investigated as a function of defect size. Critical defect sizes, therefore, for a given applied loading regime, could be obtained for each of the materials.

Keywords: Lifting Chains, Quasi-Static Fracture Toughness, Dynamic Fracture Toughness, Engineering Critical Assessment (ECA).

INTRODUCTION

Current ISO and CEN product standards for high strength lifting chain are material specific rather than performance based. There are no toughness requirements contained within the current BS EN standard for ‘short link chain for lifting purposes - safety’[1]. The main test criteria are based on the application of a manufacturing proof force, MPF (of at least 2.5 times the safe working load limit (WLL)) and subsequent examination by competent persons.

The development of future standards may be based on performance, thus there is a possibility that toughness specifications, in terms of Charpy energy requirements, may be included in ISO chain standards. In the past, such values have been based on “engineering judgement” rather than fracture mechanics considerations. Using the latter, it is possible to define a minimum fracture toughness level for a particular component such that, in the presence of a typical defect, failure will not occur at the safe working load. Conversion to an appropriate Charpy value, which can then be written into standards, can be achieved using a suitable correlation, if available. This approach is used in many industries to define appropriate levels of toughness as there is general recognition that fracture toughness tests are too complicated and/or too expensive to be included in standards.

Boron steel is used in the manufacture of lifting chain in a number of countries, however, the performance of boron steels has not been fully documented. Boron steels are known to exhibit good levels of hardenability and adequate mechanical properties. The fracture toughness properties of these materials, however, has not been fully explored. This paper deals with the :

(i) determination of fracture properties of grade 8 low alloy and boron steel chain material; and
(ii) development of performance criteria for grade 8 chain material to replace existing material specific requirements.

MATERIALS

Three materials were selected for investigation. The materials chosen were: (i) an alloy chain steel containing 0.31% chromium, 0.57% nickel and 0.30% molybdenum, designated material A; (ii) a low alloy 1.5% manganese Japanese boron steel designated material J; and (iii) an EU manufactured low alloy boron steel, material B. The material was provided in the form of 13mm bar, heat treated by a chain manufacturer to achieve the relevant material properties. The chemical analysis of these materials is shown in Table 1. Only material A met the requirements outlined in BS EN 818-2,1996, i.e. contains at least 0.4% Nickel. Materials B and J contained very low levels of both molybdenum and nickel compared to the alloy steel. Materials B and J also contained relatively high levels of sulphur and phosphorus, respectively. It should also be noted that materials B and J contained similar levels of Boron. In the case of the alloy steel the very low Boron level is likely to be a tramp element rather than a deliberate addition. All three materials exhibited similar tempered martensitic structures, however, the structure of material J was somewhat coarser than the other two materials.

TABLE 1
CHEMICAL COMPOSITION OF CHAIN MATERIALS

Material	C	S	P	Si	Mn	Cr	Ni	Mo	Cu	Ti	B
A	0.251	0.003	0.005	0.301	1.57	0.317	0.590	0.307	0.03	0.004	0.0009
J	0.249	0.003	0.016	0.272	1.47	0.135	0.017	0.017	0.02	0.011	0.0035
B	0.22	0.013	0.005	0.204	1.04	0.246	0.036	0.036	0.08	0.046	0.003

EXPERIMENTAL AND RESULTS

Charpy Impact Energy

Sub-standard (9x9mm) specimens were tested in accordance with the Charpy 'V' notch testing standard [2]. The tests were performed over a range of temperatures between -40°C and +20°C (likely to cover the operational range of high strength chain materials). The Charpy impact transition temperature data is shown in Fig 1.

For many weldable structural and wrought steels, a minimum Charpy impact toughness requirement of 27J (0.34 J/mm^2) (~ 21J when corrected for the effect of using 9 x 9mm Charpy specimens) is specified. Materials A and B exhibit good levels of toughness over a wide range of temperatures - approximately 25J at -40°C and 50J at 20°C. Even at temperatures as low as -20°C these materials exhibited lower bound

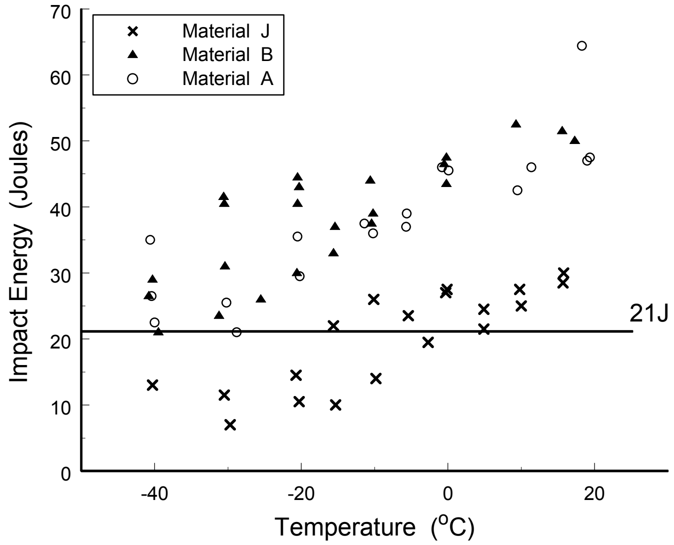

Figure 1 : Charpy Impact Data for all Three Chain Steels

toughness values well in excess of the 21J level. In contrast to the other materials it is evident from the Charpy impact data, that the J material exhibited much lower toughness levels over the whole test temperature range, i.e.10J was obtained at -40°C and 28J at +20°C, with the lower bound toughness data only exceeding the 21J level at ~5°C. In this case, the brittle fracture surfaces exhibited significant areas of low energy intergranular fracture, as shown in Fig 2. It should be noted that both cleavage and intergranular fracture were apparent even at the highest test temperatures (approaching room temperature).

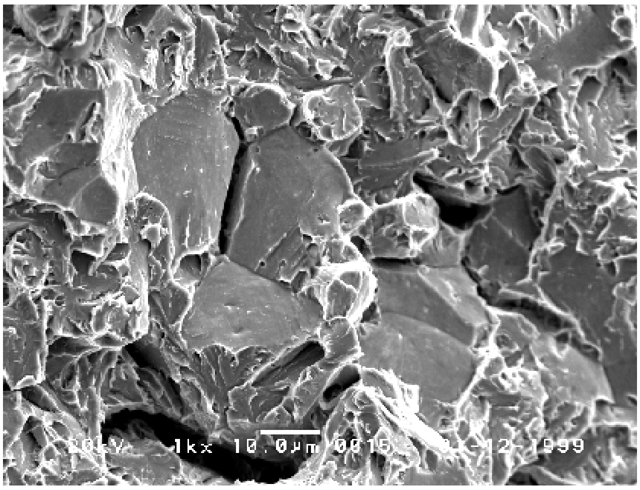

Figure 2 : Example of Intergranular Fracture Observed in Chain Material J

Fracture Toughness

A number of single edge notched bend (SENB) specimens, 9x9mm in section, were machined from each of the materials. It should be noted that a 60° notch was used rather the normal 45° (used in Charpy impact testing) to aid in the initiation of a fatigue pre-crack. The specimens were pre-cracked under fatigue conditions to create a sharp ~4.5mm long crack, suitable for fracture toughness testing.

Quasi-Static Fracture Toughness

All quasi-static tests were carried out on a servo-hydraulic test machine over a temperature range expected to produce both upper and lower shelf behaviour in these materials. Displacement during the tests was monitored using (i) a transducer connected to the actuator; and (ii) a calibrated clip gauge which was attached to the mouth of the test specimen. During each test, the applied load together with both displacement data outputs were captured for further analysis. These tests were performed in accordance with the British Standard BS 7448 for conducting fracture toughness tests [3]. In order to derive full ductile-brittle transition temperature (DBTT) curves for the three materials, the amount of ductile crack growth prior to cleavage (measured using a scanning electron microscope) was plotted against temperature, as shown in Figure 3. (It should be noted that this approach was utilised, as excessive data scatter was obtained when plotting fracture energy as a function of temperature).

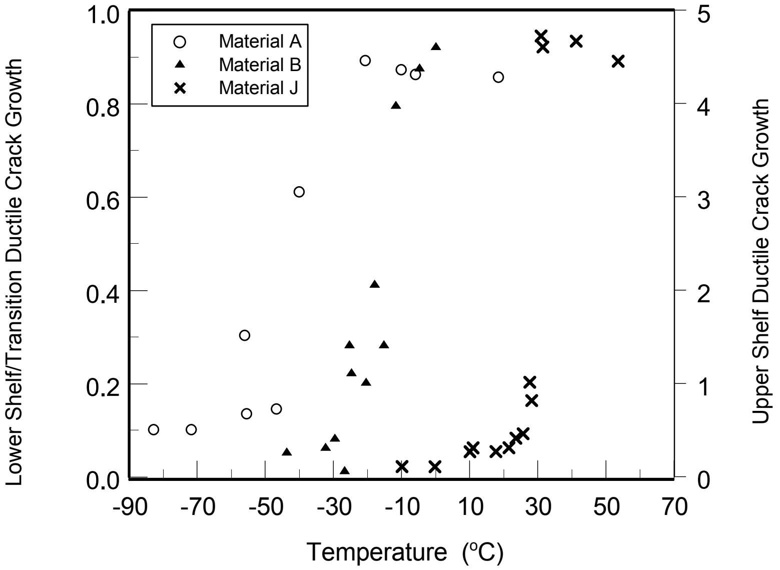

Figure 3 : Quasi-Static DBTT Curves Obtained for Materials A, B and J

The transition temperature range for material A appears to be from -50 to -35°C and for material B from -30 to -15°C. The DBTT curve obtained for material J indicates that even at ambient temperatures, lower transition behaviour will be exhibited.

Dynamic Fracture Toughness

All dynamic tests were conducted on an instrumented falling weight impact machine. Impact forces (F) were measured using a piezoelectric force transducer mounted just behind the striker mass. From the force (F) and the striker mass (m), the acceleration was calculated and by double integration of the acceleration, the displacement during the impact test was obtained. The specimens were loaded in three point bending using a mass of 12.9kg with an impact velocity of 2m/s. Dynamic fracture toughness, J, was calculated from the energy under the load-displacement curve using the methods outlined in BS 7448 [3]. Figure 4 shows the dynamic fracture toughness results, plotted as a function of temperature. The lower shelf dynamic toughness of materials A, B and J are broadly similar, however, the upper shelf toughness of material A is some 60% higher than that of materials B and J.

DISCUSSION

Fracture Properties

The Charpy DBTT curves (see Fig 1) obtained for materials A and B are very similar, which is in direct contrast to the results obtained from the dynamic fracture toughness tests, where materials B and J exhibit significantly different behaviour to that shown by material A (shown in Figure 4). The dynamic tests had been carried out on pre-cracked specimens and the differences in behaviour could be attributable to the fact that the boron chain steels (materials B and J) are particularly sensitive to defects.

Intergranular crack growth was observed on the fracture surfaces of the boron chain steels. This is a low energy mechanism and will reduce the toughness of a material and thus explains the reduction in toughness observed for materials B and J, when subjected to both quasi-static and dynamic loading conditions.

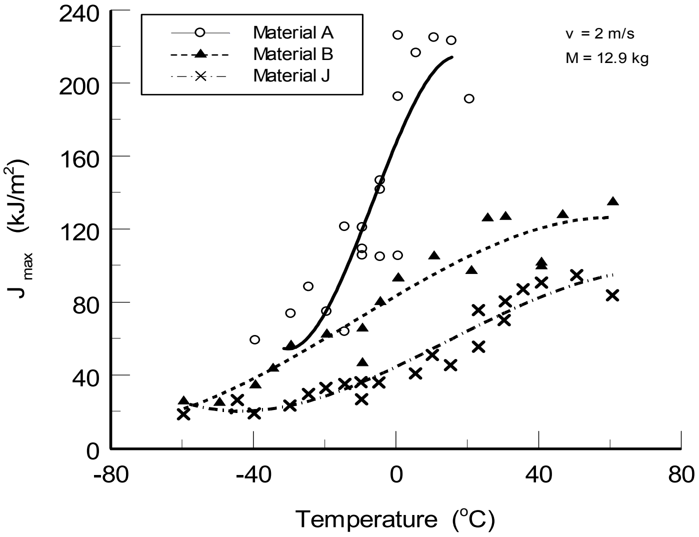

Figure 4 : Dynamic DBTT Curves Obtained for Chain Materials A, B and J

Material J contains high concentrations of phosphorus and B contains relatively high concentrations sulphur. The intergranular mode of failure, observed in materials B and J could be associated with either an accumulation of impurity elements or the formation of a film of a brittle phase on the grain boundaries and suggests that the heat treatment or the metallurgical balance of the material was not optimised.

As may be expected, under dynamic loading conditions, the effect of increasing the strain rate is to substantially increase transition temperatures obtained for the three materials. For example, for the alloy steel chain, the mid-toughness transition temperature increases from -45^{o}C, for quasi-static loading, to -10^{o}C obtained under dynamic loading conditions. This effect is not as pronounced for the two boron steels and, in the case of the J series material, upper shelf behaviour was not obtained, even at the highest test temperature (~60^{o}C). It is also evident that the upper shelf fracture toughness values obtained under dynamic test conditions for all three materials appear to be greater than those obtained from quasi-static tests conducted on similar specimens. This may be accounted for by the increase in the material yield strength associated with an increased strain rate.

Performance Criteria

The most conservative toughness (K_{mat}) values (even when compared with those obtained under quasi-static and dynamic loading conditions) were obtained using the relevant Charpy energy-K_{IC} correlations contained within Appendix J of the British Standard Guide on Methods for assessing the acceptability of flaws, BS 7910 [4]. (It should be noted, however, that the correlations contained within BS 7910 are based on Charpy impact data obtained from 10x10mm specimens). Engineering critical assessments (ECA) were performed using these conservative K_{mat} values and the methods contained in BS 7910 [4], in order to develop performance criteria for the three chain materials (allowing fracture stress to be investigated as a function of defect size).

Results suggest that at a nominal stress of 300MPa (i.e. equivalent to a WLL of 5.3 tonnes for a 13mm chain diameter [1]), materials A and B could tolerate defects in excess of 5mm in depth, even on the lower shelf, which is in agreement with results obtained elsewhere [5]. Even the worst case material (lower shelf J material), at the working load limit, was determined to be capable of withstanding a defect of ~2.8mm in depth prior to brittle fracture. It is suggested, therefore, that Charpy impact toughness values of 21J (or 0.34 J/mm^2), obtained from 9 x 9 mm sub-size specimens, and above will lead to critical defect depths in excess of 5mm for these chain materials operating at safe working load levels.

It should be noted that the safety factors [1] used in the determination of the safe working load limits for chains allow relatively large defects to exist in the chain (over the whole range of operating temperatures) prior to brittle fracture. By using non-destructive test (NDT) techniques, such as dye penetrant, therefore, such cracks should be detected before they can reach a critical size. Other NDT methods such as magnetic particle inspection (MPI) may be difficult to implement. Based on a true mean stress at the manufacturing proof force (MPF) of ~750 MPa [1], however, recalculating the critical defect sizes for material J yields values between 0.53mm (at -40°C) and 2.7mm (at +20°C). For materials A and B, the recalculated critical defect sizes ranged from ~3.0mm (at -40°C) to ~4.2mm (at +20°C). It is clear that defects, in the case of material J for example, of 0.53mm in depth could survive the MPF and would be stable at the WLL. Consideration would need to be given, therefore, to the propagation of sub-critical defects by a corrosion or fatigue mechanism, for example, and this would inform decision making on NDT or proof test intervals

CONCLUSIONS

Materials A and B exhibit good levels of Charpy impact toughness over a wide range of temperatures. Even at temperatures as low as -20°C, both materials exhibit lower bound notch toughness values well in excess of 21J. The J material exhibits much lower toughness levels, with the lower bound Charpy impact toughness data only exceeding 21J at ~5°C. In this case the brittle fracture surfaces exhibited significant areas of low energy intergranular fracture.

In general, boron chain steels (materials B and J) are particularly sensitive to crack like defects. This may be attributed to intergranular cracking along grain boundaries which occurs in these materials even during pre-cracking. It is evident therefore that the toughness and thus the defect tolerance of these boron chain steels will be low compared with that of the alloy steel chain.

K_{mat} values derived from Charpy impact data, yielded lower bound toughness values. The critical defect sizes calculated, based on these K_{mat} values (as opposed to K values based on the results from fracture toughness tests), were thus conservative.

It is recommended that chain steels should exhibit a minimum Charpy impact energy of 27J (0.34 J/mm^2) (equivalent to 21J for a 9 x 9mm sub-size specimen) over the full range of operating temperatures. This level of toughness in the parent material ensures that critical defect sizes, based on either the WLL or MPF will be large enough to be detected by current NDT techniques. Below this level, particularly for load levels approaching the MPF, critical defect sizes become relatively small and could prove difficult to detect.

ACKNOWLEDGEMENT

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REFERENCES

1. BS EN 818-2 (1997). Short link chain for lifting purposes - Safety. Part 2 : Medium tolerance chain for chain slings – Grade 8, BS EN 818-2, 1997.
2. BS 10045-1 (1990). British Standard for Charpy Impact Test on Metallic Materials. Test Method ('U' and 'V' Notches). BS EN 10045-1. 1990.
3. BS 7448 (1991).British Standard for Fracture Mechanics Toughness Tests : Part 1. Method for Determination of K_{IC}, Critical CTOD and Critical J Values of Metallic Materials. BS 7448 : Part 1: 1991.
4. BS 7910 (1999).British Standard guide on methods for assessing the acceptability of flaws in fusion welded structures. BS 7910, 1999.
5. Cadman, A. J. and Bann, P. J. (1985).'Assessment of the material properties of a high strength low alloy chain steel containing a boron addition' RLSD Section Report No. IR/L/MM/85/2. Health & Safety Executive, Research and Laboratory Services Division. Sheffield. 1985.