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The Effect of Laser Transformation Notching on the Controlled Fracture of a High Carbon (C70S6) Steel

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Abstract
A high carbon (C70S6) steel has been laser surface treated using CO_2 and Diode lasers in order to produce an embrittled region to act as a fracture notch. Such a process has been investigated as a precursor to the fracture splitting of automotive engine connecting rods. Microstructures of the treated regions have been examined and the fracture behaviour of notched samples has been quantified.

Depending on the laser processing parameters used, the laser transformation notch (LTN) undergoes either solid state transformations or a mixture of melting and solid state transformations. The effect of LTN depth on the peak impact force, the crack initiation energy and Charpy fracture energy was investigated on a C70S6 carbon steel using an instrumented Charpy impact facility. It was reduced to a value < 3.5 J by a LTN of ~ 0.5 mm in depth. Fracture mechanics models indicate that such a LTN can behave in a similar way to a fatigue created crack used in fracture toughness testing ie the LTN behaves as a sharp crack.

Obtaining a sharp crack effect from a LTN is attributable to a combination of: a) the presence of brittle martensite, b) intergranular cracking of favourably oriented columnar grains after melting with inclusions and defects at their boundaries, c) intergranular cracking of coarse grains produced by a high austenitising temperatures and d) minor or major cracks sometimes resulting in centre – line cracking which arises during solidification. LTN was thus shown to have the potential to lead to an effective means of obtaining consistent fracture splitting of connecting rods.

Keywords: fracture splitting; laser processing; laser induced phase transformation; instrumented Charpy impact testing

1. Introduction
Lasers are used to promote melting and / or solid state transformations [1] in a number of metal processing activities eg in cutting, welding and surface treatments [2]. In most of these operations, the strength and toughness of the material is maintained or improved after laser treatment [3]. When using laser technology in the manufacture of engine connecting rods the aim is to embrittle the material locally and thus initiate fracture and allow the cap part to be split away from the big end of the rod.

Originally con-rods for internal combustion engines were manufactured by a combination of forging, cutting, drilling and machining. The cap, after being cut away from the rod, was machined on the cut faces to allow the joints to be bolted together on flat contact surfaces. Fracture splitting was developed in the 1990's to reduce costs and to deal with concerns over the load bearing ability of machined surfaces [4]. In the splitting operation the cap is fractured with minimum plastic deformation. The uneven but seamless fitting of the fracture faces together provides an increased total joint surface area [4] when they are bolted together before final machining of the bore.

Steels used for con-rods require good fatigue strength and machinability. Medium carbon steels have been used in the quenched and tempered or as-forged and air cooled condition to give these properties. The fracture splitting process was initially applied to more costly, but less ductile powder forged steels, as the cast and forged steels were too ductile to ensure effective crack initiation and propagation. A more recent move is to use 0.7wt% carbon cast and forged steels, e.g. C70S6, which are spittable, but less costly than powder forgings [5, 6, 7].

The conventional fracture splitting technique required a sharp notch about 0.5 mm deep, to be mechanically broached on either side of the big bore. The variability of broaching tool geometry with use played a significant role in the sharpness of the notch. Any resultant plastic deformation associated with the cracking process adversely influenced the ovality or roundness of the split con-rods. A further disadvantage was the necessity for frequent tool maintenance. The key advantage of introducing laser notching is that the notch is generated by a non-contact process, thus eliminating tool wear problems and the need for maintenance.

Alfing Kessler Sondermaschinen GmbH [4] and Albon plc [8] have used laser drilling (LDN) and laser scribing methods respectively to create notches for fracture splitting. In both cases the notch was created by laser induced material removal.

This paper investigates the underlying processes which are associated with a completely different approach to laser notching. Instead of removing material to create a notch, the laser simply induces phase transformations which result in localised embrittlement, hence enhancing the ability to fracture. Since material is not removed, contamination by molten debris ceases to be a problem, as it is in both the Kessler and Albon techniques. Another advantage is speed, as the LTN process requires only 3s (plus transfer time) to notch both sides of a con-rod, compared to a time of approximately 20s required for laser scribing in the double-pass Albon technique. The important step in the new technique is to change microstructure by melting and solid state transformations. The aim of this paper is to report processing-microstructure-property relationships.

2. Experimental

2.1. Materials

Drop forged C70S6 steel con-rods were supplied from which 10 x 10 x 55 mm specimens (Charpy impact specimens with no mechanical notch) were cut from the big end of each rod in the region where fracture splitting would occur. The composition of the steel is listed in Table 1. The specimens were ground to a surface roughness Ra = 0.6 ± 0.008 μm perpendicular to the grinding direction and 0.23 ± 0.03 μm parallel to the grinding direction.

2.2. Laser and other heat treatments

Impact test samples were scanned by a continuous laser beam with a single pass at the normal V-notch position to form a LTN whose depth and width vary with the laser beam size, power and transverse velocity. The correlation between laser notch depth and the processing parameters is discussed elsewhere [9].

Two different lasers were used in this work: a 4.0 kW CO_2 laser with a Gaussian beam focused to a diameter of 1.0 mm and a 2.0 kW diode laser with a rectangular spot size approximately 2.0 x 6.0 mm in focus. The diode laser spot had a top hat intensity distribution in the direction parallel to the 6.0 mm edge and a Gaussian distribution in the perpendicular (2.0 mm) direction. Relative motion of the diode laser and sample was parallel to the 6.0 mm beam dimension, resulting in a track width determined by the 2.0 mm (Gaussian) dimension of the beam. Most of the data reported here came from notches produced by the CO_2 laser.

All laser notching was conducted in air at ambient temperature. The ground surface of the steel samples was cleaned in ethanol prior to laser treatment. No coatings were used on the sample for enhancing absorption of the laser beam.

To promote further understanding of the subsequent failure mechanisms, selected LTN specimens were also subjected to two different post heat treatments, ie tempering at 550 °C for 15 minutes followed by furnace cooling and normalising at 1000 °C for 15 minutes followed by cooling outside the furnace. All post – notching heat treatments were carried out in an argon protective environment to avoid oxidation and decarburisation.

2.3. Mechanical testing

Impact tests were carried out on an instrumented IMATEK Charpy impact tester. A strain gauge transducer detected the impact force applied on the front edge of the pendulum hammer where it contacted the Charpy specimen. Sampling frequency was 667 kHz for all tests. Frequency filters were not applied to the collected data sets because the instrument was calibrated in such a way that the calculated total impact energy from the unfiltered impact curves match closely with the absorbed energy from dial reading. Frequency filters could also distort the curve. Displacement was calculated by the software from the time of the initial impact to that of complete fracture. The instrument met all the requirements listed in BS EN ISO 14556-2000. A microhardness tester was used with a 300 g load to determine hardness variations in the heat affected zones of the samples.

2.4. Microstructural characterisation

Cross-sections of the laser notches were examined using optical and scanning electron microscopy (SEM) used in secondary electron and back scattered image modes. Samples were etched in a 5vol% picric acid solution. EDX analysis was employed to obtain the composition of inclusions etc. Fractography of the failed specimens was carried out using SEM.

3. Results

3.1. The geometry and microstructure of the laser notches

The microstructure of the as-forged C70S6 steel consisted of pearlite grains with ferrite at their boundaries (see Figs. 1a and 9b). The term "laser transformation notch" refers to the area which can be clearly distinguished from the bulk material on etched cross sections (Fig.1) and from hardness tests (Fig. 2).

CO_2 laser notching was carried out with a beam diameter of 1.0 mm operating at 1.0 kW power which traversed the steel surface at different speeds of 1.0 m min^{-1}, 2.0 m min^{-1}, 3.0 m min^{-1}, 4.0 m min^{-1} and 4.5 m min^{-1}. The corresponding LTN depths were measured at 0.35 mm, 0.22 mm, 0.14 mm, 0.08 mm and 0.07 mm. Fig.1a shows the cross section of the notch which was produced with the CO_2 laser at the highest (4.5 m min^{-1}) traverse speed. The notch consists of a single zone of martensite produced without melting. Melting was observed in samples which were notched at the two slowest traverse speeds. These resolidified regions are characterised by columnar grains (as can be seen in Figure 1b) together with centreline cracking. The formation of the columnar grains results from rapid heat extraction from the melted pool by the large volume of the surrounding unheated material. This notch was produced by operating the diode laser at 1.9 kW beam power and a traverse speed of 0.5 m min^{-1}.

More detailed features are shown in Fig 3 of a LTN with a resolidified region produced using the CO_2 laser operating at 1.0 kW power and at a traversing speed of 1.0 m min^{-1}. Fig. 3a demonstrates the presence of the resolidified region 1 and the solid state transformation region 2 which is surrounded by the original forged microstructure (region 3). Resolidified columnar grains shown at high magnification (Fig. 3b) in region 1 have an average width of ~ 7.5 µm. The orientation of these grains was determined by the direction of the laser beam passing across the sample surface and the direction of heat extraction through the bulk material. EDX analysis in the SEM confirmed that the particles visible at the columnar grain boundaries are MnS. As well as inclusions, there are voids at the columnar grain boundaries, which may have resulted from the MnS particles being removed during sample preparation. After resolidification, the steel in region 1 continues to cool at a sufficiently high rate to transform completely to martensite. Immediately below the resolidified material a coarse austenitic grain size exists in region 2 due to rapid grain growth at high temperatures, see Fig 3c. Martensitic plates are larger in size in these coarse grains than in the remaining part of region 2 which was transformed to finer austenite grains at lower temperatures during laser treatment. The boundary between the laser notch and the parent steel (region 3) is shown in Fig. 3d, where the martensite / pearlite boundary forms a sharp demarcation between steel which did and that which did not exceed ~720 °C during laser treatment. Small partially dissolved pearlitic regions can be observed (shown by the arrow), where thermal conditions were unable to fully austenitise the steel.

3.2. Hardness of the laser modified material

Fig. 2 shows the variation in microhardness (HVM) versus the depth for a laser notch which has resolidified material extending to a depth of approximately 1.0 mm. The hardness increased from HVM 285 in the (non-laser-modified) bulk material to over HVM 800 within the laser notch. Little variation of hardness occurred across the notch, because martensite is the only phase present other than inclusions in both the resolidified columnar grains as well as in the solid state transformed region. The small regions of incompletely dissolved pearlite, very close to the interface between the transformed (martensitic region) and the parent (pearlitic region) have little effect on the abrupt change in hardness.

3.3. Instrumented Charpy impact curves and their dependence on laser notch depth

Impact force-displacement curve of the Charpy specimens with laser notch depths of 0.07 mm to 0.35 mm were produced for steel samples subjected to CO_2 laser treatment at five different traverse speeds. Figs. 4a, 4b and 4c show the plots associated with samples having notch depths of 0.07, 0.14 and 0.35 mm. Fig. 4d is the force-displacement curve for the Charpy specimen notched to a depth of 1.6 mm using the diode laser at 1.9 kW and 0.5 m min^{-1} traverse velocity. Fig. 4e depicts the impact curve of a standard CVN specimen.

It should be noted that the first peak in all the graphs is recognised as an inertia peak [10,11] and is identical in amplitude and in displacement. The area under the curve designated as area (1) in Fig 4 relates to the inertia energy, which is associated with the acceleration of the stationary specimen to the velocity of the hammer-specimen pair. The maximum or peak force is arrowed in the plots in Fig. 4. and this is associated with crack initiation. Area (2) shown in Fig. 4 up to the peak force is taken as crack initiation energy. After initiation, area (3) in Fig. 4 represents crack propagation energy.

None of the curves showed evidence of any crack arrest in the propagation stage, as would be demonstrated by an abrupt change in slope in the force-displacement plot. The occurrence of plastic yielding prior to the peak force occurred in samples with smaller notch depths, see Figs. 4a and 4b. This resulted in an increase in maximum force due to work hardening before crack initiation. Figs. 4c and 4d are impact curves for samples which contain larger laser notches where no plastic deformation was observed prior to the rapid brittle fracture of these samples. It was noted that the reproducibility of the impact force-displacement plots prior to crack initiation is less consistent in the samples where plastic deformation has occurred but excellent when there is virtually none.

The dependence of total absorbed impact energy (crack initiation and propagation) on the laser notch depth is shown in Fig. 5a where the 1.6 J energy represented by the inertia peak has been removed. The two curves are for impact samples notched by the CO_2 laser and the diode laser respectively. The main difference between the two different notches is the width at the surface. The diode laser notches were much broader than those produced by the CO_2 laser due to the larger beam width of the diode laser with sufficiently high power intensity. The measured impact energies for the diode laser notches $\geq$ 0.5 mm deep is below 3.5 J which are close to those produced by the CO_2 laser. This suggests that the width of laser notch has only a minor role in the initiation of unstable cracks. In comparison, the CVN specimens had a dial reading impact energy of 4.8 J after taking away the inertia energy and its dial reading is 6.4 J.

Figs. 5b and 5c show plots of the peak force and peak energy versus the depth of notches produced by CO_2 laser. Peak force and peak energy are regarded here as the critical force and energy to initiate unstable brittle cracks.

3.4. Fractography

Three major features were observed on the fracture surfaces of LNT Charpy specimens. These are (i) the intergranular cracking at columnar grain boundaries in the resolidified zone, (ii) the intergranular cracking of the coarse grains at locations where the austenitising temperature was high and (iii) the transition to transgranular martensitic fracture, see Fig. 6a, in which the specimen had a notch depth of 0.35 mm.

With larger notches (>0.14 mm) the columnar grained regions fractured intergranularly, see Fig. 6b. Coarse equi-axed grains can be seen to fracture intergranularly at higher magnification (see Fig. 6c) close to the columnar boundary.

The finer martensitic material below the coarse grains has undergone transgranular fracture (Fig. 6d). Finely distributed inclusions can be observed at the columnar grain boundaries (see Fig. 6b).

At smaller notch depths ie less than 0.14 mm columnar grains were not formed and thus the surface region of coarse martensitic grains failed in an intergranular manner (Figs. 7a and 7b) and an underlying region of fine martensite failed in a transgranular manner.

Fig. 8 depicts the fracture surface of CVN specimen. There is a plastically stretched region immediately beneath the root of the V-notch (see Fig. 8a). The area adjacent to this region also showed ductility before cleavage fracture started (Fig. 8b).

3.5. Influence of tempering or normalising laser notches on impact properties

Table 2 shows the Charpy impact energy of as-notched, notched and tempered and notched and normalised C70S6 specimens.

The influence of tempering on the Charpy impact energies of laser treated samples varies significantly. With the sample containing a deep notch (0.63 mm), tempering has had a relatively minor effect which implies that the tough heat treated matrix has increased the fracture energy by a significant amount ie. from 3.1 to 14.8 J. Decreasing the notch size and more particularly the depth of the melted zone from 0.46 to 0.13 mm promotes a major increase in fracture energy from 14.8 to 78.9 J. But this still implies that embrittling features are maintained in the resolidified zone and their effect reduces with the zone depth. The tempered martensitic structure has its full effect when the melted zone reduces to zero with a notch depth of 0.08 mm and the sample did not break.

Normalising the laser notched samples produced a big change to all small and large notch samples. Even with the presence of a large melted zone the fracture energy is raised from 3.1 to 61.8 J, which implies that reaustenitisation at 1000 °C produces changes to the source of embrittlement. When the melted zone in the notch is small or non-existent, then the normalising treatment effectively removes all embrittling mechanisms and restore the samples to resist fracture.

Optical images of cross sections of the tempered and normalised specimens are shown in Figs 9a and 9b. The visible size of the notched region is not significantly reduced by the tempering treatment, but normalising removes region 2 which has been subjected to a solid state transformation alone during laser heat treatment. The melted zone in the normalised sample remains in view despite changing its grain structure. This was brought about by a transformation to fine austenitic grains which subsequently on slow cooling has produced a fine grained pearlitic-ferritic structure, which has effectively removed the aligned columnar grains. Secondary electron images (SE) reveal large pearlitic - ferritic grains in the bulk material and in region 2 but has refined pearlitic-ferritic grains in the melted regions of the normalised samples, see Figures 10a and 10b. Corresponding to the change in microstructure, the normalised notch region has returned back to a value close to the bulk hardness. Figs 10c depicts back scattered electron (BSE) images of an as–notched and normalised samples with evidence of aligned MnS particles (arrowed) at original columnar grain boundaries. Pearlite grains also now exist across the original columnar boundaries, indicating that during normalising austenite grains have renucleated and repaired the weak boundaries. Some evidence of microcracks about 150 μm long were observed close to the surface of the melted region (see Fig. 10d).

Fig. 11a depicts the fracture of sample with a large laser notch after tempering at 550 °C for 15 minutes. At this low magnification it is very similar to the as-notched fracture as shown in Figure 6a. The columnar grains still exist but their boundaries become more ductile as revealed in Fig. 11b. By tempering, the intergranular fracture in the large equi-axed grains (see Fig. 6c) was replaced by a ductile transgranular fracture.

Normalising has eradicated both the intergranular fracture of columnar and large equi-axed grains. Figures 11c and 11d depict the ductile fracture where the previous columnar grains existed.

4. Discussion

Consideration will be given here to a number of issues which needed to be raised on the results of the laser treatment of the C70S6 steel samples and in the subsequent Charpy impact tests carried out upon them. The topics to be discussed are:-

- providing a fracture mechanics basis for the interpretation of the measurements made during the instrumented Charpy impact tests on LTN notched samples.
- analysing the microstructure and impact data to specify the key embrittling mechanisms which control fracture in the LTN as the depth of laser treatment increases.

4.1.Relationship between LTN dimension and peak force

4.1.1. Establising a correlation between Charpy impact energy and Fracture toughness

It is necessary to consider how fracture toughness (K_Ic) tested under slow bend conditions could relate to standard Charpy impact energy (CVN). Clausing [12] showed that the state of the stress at fracture initiation in a Charpy impact test sample is plane-strain as is also the case with samples undergoing K_{Ic} testing. Nevertheless, two correlations have been developed between these measurements on an empirical basis and these are dependent on experimental data obtained on a range of carbon and alloy steels [13,14]. One of these relates to steels which exhibit fibrous fractures when the test are carried out at temperatures close to that of the upper shelf. The other concerns tests conducted at or near lower-shelf temperatures where fracture takes on a cleavage form. In the case of high carbon C70S6 steel in the as-hot worked condition the ductile-brittle transition takes place at relatively high temperatures, ie the lower-shelf will remain at temperatures in excess of 40 ºC. This is strongly influenced by the prior austenite grain size and the percentage of pearlite present [15, 16]. Hence, with a standard Charpy test carried out at 20 ºC the fracture is going to be a brittle cleavage type.

Barson and Rolfe [13] obtained a relationship between K_Ic under slow bend conditions and CVN under impact loading conditions from a series of experiments in the ductile-brittle transition zone on a group of structural steels with varying yield stress values. The equation took the form

$$K_{Ic}^2 = 0.22 \cdot E \cdot (CVN)^{1.5} \qquad (1)$$

where E the elastic modulus for the steel, K_{Ic} is the plane strain fracture toughness in MPa√m and CVN is the Charpy impact energy from dial reading given in MPa m.

In the cleavage fracture condition which exists at such test temperatures, strain rate and notch acuity become important variables and would therefore influence equation (1). The effect of loading rate on CVN specimens was investigated [13] on the structural steels and this demonstrated a shift of the absorbed CVN energy – temperature plot to higher temperatures at higher loading rates. The magnitude of the shift was influenced by the yield stress of the steel concerned, so that a gradual reduction occurred as the yield stress rose to 950 MPa, at which stage it became negligible. A similar temperature shift has been observed by Shoemaker and Rolfe [17] with K_{Ic}- temperature as a function of loading rate. Therefore it could be concluded that if a steel had a high enough yield strength and was tested with a notch of appropriate acuity at a temperature close to its lower shelf value, the correlation stated in equation (1) would apply.

More recent work by Sudhakar and Murty [18] has demonstrated a close agreement between measured and calculated values of K_{Ic} for a 0.64wt% carbon steel using standard Charpy data in equation (1). This steel is close to the composition of C70S6 used in the current work. The yield strength of both steels are in the range 650 – 700 MPa which would fall below the 950 MPa value quoted by Barson and Rolfe [13] for minimising the shift of the impact energy – temperature plot brought about by increased loading rate. At a yield stress of 650 MPa the forecast shift of 39 ºC would be significantly compensated by the temperature of the test (approximately 20 ºC) which would be below the transition temperature for a 0.7wt% carbon steel in the normalised condition.

Hence, the major variable in respect of the Charpy tests carried out on the LTN samples of C70S6 steel will be the nature of the notch ie its length, acuity and the fracture properties of the transformed phases ie high carbon martensite containing weakening influences such as aligned columnar grains.

4.1.2. Calculating the K_{Ic} value of C70S6 steel from CVN data

The absorbed CVN energy of C70S6 with standard notch of 2.0 mm in depth is 6.4 ± 0.4 J on dial reading. This can be converted to = 0.08 ± 0.004 MPa m by dividing the absorbed impact energy by the effective area of cross section of the specimens. Substituting this value into equation (1) gives K_{Ic} = 31.7 ± 3.3 MPa√m, where the error band gives a confidence interval at 95% confidence level of normal distribution. This value can be compared with 47.5 MPa√m [18] that has been obtained by conventional fracture toughness testing of a somewhat lower carbon steel (0.64%) in the normalised condition.

4.1.3. Estimating the peak forces and comparing them with measured data

A relationship between peak force (F) at the onset of brittle crack extension and notch depth (a) for a three-point slow bending test with a sample having an fatigue generated edge crack can be obtained using an equation specifying the stress intensity factor $K_I = K_{Ic}$ [19].

$$K_1 = K_{1c} = \frac{F \cdot S}{B \cdot W^{1.5}} \cdot f\left(\frac{a}{W}\right) \tag{2}$$

Where F is in kN, S is the span between the outer loading points in three point bend test, B the specimen thickness, W the effective width of test specimen, a the depth of crack and f(a/W) is a function of a/W and can be expressed as:

$$f\left(\frac{a}{W}\right) = \frac{3\left(\frac{a}{W}\right)^{0.5}\left[1.99 - \left(\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)\left(2.15 - \frac{3.93a}{W} + \frac{2.7a^2}{W^2}\right)\right]}{2\left(1 + \frac{2a}{W}\right)\left(1 - \frac{a}{W}\right)^{1.5}} \tag{3}$$

To determine the values of F using equation (2) for the case where the samples have been subjected to LTN, the values of a = LTN depth and K_{Ic} = 31.7 MPa√m for the forged C70S6 steel have been introduced. These values have been plotted in Fig. 5b as F versus LTN depth. From Fig. 4 which plots the force-displacement curves for the instrumented Charpy impact tests, the peak force has been selected as the experimentally determined value of F for the LTN samples and also plotted in Fig. 5b. The measured and calculated forces (F) are shown to be in very good agreement. An analogous relationship also exists between the peak (initiation) impact energy and LTN depth as shown in Fig. 5c. The results indicate that LTN in this high carbon steel have an equivalent acuity similar to fatigue created sharp cracks.

4.2. Fracture mechanisms with increasing LTN depth

It should be noted that LTN less than 0.4 mm deep do not have any macro centreline cracks. As shrinkage induced centreline cracking was not present it did not influence the trend of the locus in Fig. 5b, with the exception of the sample with a LTN depth of 1.6 mm. The effectiveness of the LTN on brittle fracture was clearly illustrated by considering impact tests on unnotched 10 x10 x 55 mm samples of C70S6 steel which did not break and only suffered plastic deformation. The presence of a 0.07 mm deep LTN allowed fracture with only a small amount plastic deformation. This indicates that initiation of brittle fracture does not depend on the presence of centreline cracking, but when it is present it does contribute.

The fracture in the absence of centre line cracking is therefore influenced by the following microstructural features:

- The presence of the high carbon martensite throughout the notch.
- The aligned columnar grains with associated inclusions, impurities and other defects.
- The presence of coarse grains at the surface or at the edge of the melted zone.

Both of the last two features encourage intergranular fractures.

When the depth of the notch is less than 0.12 mm, ie at lower levels of heat input, no melting takes place. In the zone where heating above the eutectoid temperature has occurred the resultant austenite transforms rapidly to martensite on cooling by the bulk of the sample. Also at the surface of the notch the laser has promoted high austenitising temperatures and thereby grain growth. The fracture energy associated with this shallow martensitic crack falls to 12 J, indicating the potential of the martensite and the surface layer of coarse grains in this 0.7wt% carbon steel to initiate a brittle crack. Beyond a martensitic notch depth of 0.12 mm, the heat input leads to melting and the introduction of another embritling mechanism ie, aligned columnar grains which also rapidly cool to form martensite. Hence, when the fracture energy decreases further ie. $\leq$ 4 J with LTN depths greater than 0.4 mm there are all four embrittling mechanisms at work ie centreline cracking, columnar grains, coarse grains and brittle martensite. The coarse grain region continues to form in notches deeper than 0.12 mm at the edge of the melted zone.

The use of post - laser notching heat treatments ie tempering and normalisation has demonstrated the potential of columnar and coarse equi - axed grain regions to embrittle. Tempering at 550 °C promotes carbide precipitation and reduced metastable carbon solubility in α - iron in the whole notch and thus a major improvement in toughness in the steel. The fracture energy of a C70S6 sample notched to a depth of 0.63 mm on tempering has allowed a recovery in energy from 3.1 J to 14.8 J, see Table 2. This still represents a major reduction in fracture energy from the unnotched steel sample which does not fracture. Microscopic examination of the fracture surface and adjacent regions reveals the role of the aligned columnar grains which remain after tempering, see Figs 9a and 9b. Such grain boundaries containing trace impurities and aligned non-metallic inclusions are weakened and thus promote intergranular cracks. However the coarse grain region at the edge of the molten zone does not promote intergranular cracks after this treatment. Reducing the notch depth from 0.63 mm to 0.24 mm curtails the depth of the columnar zone from 0.4 mm to 0.18 mm, which results in the tempered fracture energy rising to 79 J. Finally removing the columnar grains with a total notch depth of 0.08 mm renders the sample unbreakable. From these observations there is strong evidence in the as – notched condition, that the intergranular fracture of aligned columnar grains does assist with the fracture initiation process even when there is an increased depth of martensite present.

Raising the post heat-treatment temperature to 1000 °C has now permitted the martensite to transform back to austenite. On slow cooling, the austenite transforms to a fine grained pearlitic structure with some ferrite present. Impact testing the sample with a 0.63 mm deep notch raised the fracture energy to 62 J (Table 2), which indicates the presence of considerable ductility but it does not return the steel to the impact resistance of the un-notched steel. With reduced notch depth (0.24 and 0.08 mm) normalising does return the sample to the unbreakable condition. The fracture surfaces of both samples (0.63 and 0.24 mm notch depth) show no evidence of aligned columnar grains as the austenite grains have re-nucleated and grown at 1000 °C. Further examination of the normalised sample with 0.63 mm notch depth does reveal that aligned MnS inclusions still exist at prior columnar boundaries even though austenite grains of renucleated across the boundaries. Evidence of some short cracks (~150 μm in length) in the original laser melted region were observed, see Fig. 8d. These two factors together influence crack initiation in the normalised samples provided the LTN containing a significant melted region. The removal of major factors such as martensite and intergranular fracture of the aligned columnar and coarse grains has considerably reduced the previous level of embrittlement.

It is worthy to note that the notches produced by the Kessler ‘laser drilling’ process have been sectioned in this work and have revealed a rounded profile at the base of the hole, which would reduce the geometrical potential to initiate a crack. However, the metal immediately below the notch has been observed to show evidence of aligned columnar grains in a melted zone. The depth of this zone – 0.03 mm is much less than that produced in a LTN described here. Nevertheless, it is believed that this melted zone does assist the fracture process in association with the 0.5 mm ‘drilled hole’. The effect of these short martensitic columnar grains will be smaller in comparison with that achieved in the LTN notched samples.

5. Conclusions

The fracture is therefore influenced by the following factors:

1. The laser transformation notched C70S6 steel can have a significant lower Charpy impact energy than that generated by mechanically notching.

2. Laser transformation notching can improve upon mechanical broaching process for fracture splitting con-rods and provide more consistent results as broaching tools require periodic sharpening.

3. Fracture mechanics analysis based upon the presence of a sharp fatigue notch has demonstrated that laser transformed notches in high carbon steels are equally effective in reducing the crack initiation force.

4. Combinations of laser power and its speed of movement across the steel surface control the heat input and thus the depth of transformation, ie to promote solid state transformation to martensite and then melting.

5. The major factors in reducing fracture energies down below 3.5 J and virtually eliminating plastic deformation with a 0.45 mm LTNare martensite formation and the intergranular cracking of aligned columnar and coarse equiaxed grains when a molten zone is formed.

6. Micro- or macro- cracking can be associated with the molten zone eg centreline cracking due to contraction; such cracking when present in the larger LTN also can contribute to the reduction in fracture energy.

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