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Laser-glazing low carbon iron fracture samples

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Charpy samples of low carbon steel were laser-glazed in the V-notch root, resulting in highly modified fracture properties and radially altered crystal structure. Laser-glazing produced two distinct regions: (a) an inner region, next to the bulk material, which was heated above the austenitic transition temperature, was cooled rapidly, and produced a retained austenitic phase, and (b) an outer region, next to the V-notch surface, which was heated above the melting temperature, cooled more slowly, although still very rapidly, and transformed predominantly into the martensite phase. Instrumented impact testing of laser-glazed samples produced fracture energies and fracture toughness values similar to samples prepared by currently accepted ASTM precracking procedures. Laser-glazing is offered as an alternative to existing procedures as an experimental technique for testing fracture toughness samples and, especially, for testing substandard size samples and hard-to-prepare, fracture toughness materials samples.

1. Introduction

High energy lasers have been used to interact with material surfaces and produce extraordinary results including: phase changes, grain refinement, amorphous structures, and unusual alloys [1–8]. Laser-glazing, or laser surface modification, affects a very limited volume of material and produces an extremely shallow interaction zone. The high energy of the laser beam results in a highly altered, unstable, and highly stressed region of material, which remains in integral and continuous contact with the unaffected bulk material. Interaction of lasers with ferrous alloys is currently used both in research [9–11], and in industry [12, 13] to alter the base material structure and to harden surfaces. Such interactions can produce internal stresses high enough to buckle, and even fracture, the bulk material. Kow *et al.* [14] and Christodoulou *et al.* [15] have conducted a thorough analysis of the affects of laser-glazing on carbon steels.

In the current study, two low carbon steels were laser-glazed in the root of the V-notch of Charpy samples. The laser was of high enough energy to melt the surface of the V-notch and introduce to the region a microweld zone. The laser-glazed Charpy samples then had the same structure as a microdrop weight-test sample, with the laser melt region acting as a microweld. This highly stressed, highly modified structure initiated an atomic size crack into the low strength, ductile bulk material during an instrumented impact test. Results suggest that laser-glazing offers an excellent alternative to precracking samples for fracture toughness testing (20 samples).

2. Experimental details

Twenty standard Charpy samples were prepared. Six from an AISI 1018 and 14 from an AISI 1040 hot rolled, nonalloyed carbon steel. Seven of these samples were precracked according to ASTM E-399 specifications. Seven other samples were laser-glazed in the V-notch root with a 950 watt CO_2 laser in a pulsed mode rate of 0.001 sec on and 0.002 sec off and with a travel speed of 67 mm sec^{-1}.

Samples were dynamic fracture tested at three temperatures, one from each of the three regions of the Charpy failure energy curve for an AISI 1040 steel: brittle (on lower shelf), transition, and ductile (on upper shelf). All samples were tested in

TABLE I Sample preparation, test condition and fracture results

Material	Test conditions	Test temperature (° C)	Sample preparation*	(a/W)	Normalized failure energy (J m^{-2})	K_I (MPa m$^{1/2}$)
AISI 1014	Slow Bend	−43	LASER	0.251	32.4	321
			PCVN	0.450	13.2	226
	Impact	−43	CVN	0.203	37.5	–
			LASER	0.221	1.5	43
			PCVN	0.472	1.4	55
		21	CVN	0.203	58.1	–
			LASER	0.208	55.0	404
			PCVN	0.480	39.0	394
AISI 1040	Slow Bend	21	CVN	0.203	8.8	–
			LASER	0.220	10.3	181
			PCVN	0.452	3.5	113
	Impact	−43	CVN	0.203	5.9	–
			LASER	0.208	0.6	24
			PCVN	0.470	0.7	42
		21	CVN	0.203	14.5	–
			LASER	0.264	2.4	55
			PCVN	0.470	2.4	63
		100	CVN	0.203	13.9	–
			LASER	0.249	12.3	170
			PCVN	0.444	6.9	138

*CVN = Charpy V-notch, LASER = Laser-Glazed, and PCVN = Fatigue precracked Charpy V-notch.

a three-point bend configuration on an instrumented drop-weight, impact test apparatus.

Scanning electron microscopic and optical metallographic examinations were conducted on the V-notch region of the laser-glazed Charpys after fracture. Microhardness measurements were taken across a polished cross-section from the centre of the laser-glazed region to the bulk or unaffected material region.

3. Data

Fracture energy and stress intensity values of fracture toughness results for the various sample preparations, testing temperatures, and testing conditions are summarized in Table I.

A schematic drawing of the laser-glazed V-notch region of the Charpy is shown in Fig. 1. Also pictured is a pop-in crack resulting from a slow three-point bend test which was interrupted immediately after crack initiation. Numerical values are diamond pyramid hardness (DPH) values (100 g load).

4. Results

Experimental results will be subdivided into three sections: microstructure, crack initiation, and failure values. Results of laser-glazing the AISI 1018 steel for both microhardness and structures are similar to those reported by Kow *et al.* [14].

4.1. Microstructure

Laser-glazing introduced a highly modified, high hardness structure into the V-notch root of standard Charpy samples approximately 0.5 mm deep (Fig. 2). The melt zone could be characterized as "key hole" involving significant surface vaporization [15]. Three different material structures resulted [14, 16–18]. First was the melt zone, a fine-grained randomly oriented, martensite region. The next two zones retained the basic grain structure of the original material, with only slight grain growth and were designated heat affected zones (HAZ) I and II.

HAZ I was composed principally of martensite, with traces of retained austenite and the distinct outline of the old, unmelted grain structure. Large colonies of martensite grains were oriented predominantly in a single direction within the outline of the old grain.

In the narrow transition region between HAZ I and II, the austenite to martensite transformation has just commenced at a few grain boundaries. Many of the austenite grains in this region have fine grain martensite at the grain boundary. Some grains even have a dual structure, with martensite at the boundary and a sharp shift in phase to pure austenite (Fig. 2).

At the HAZ II–bulk material interface, another change in grain structure occurs. This transition

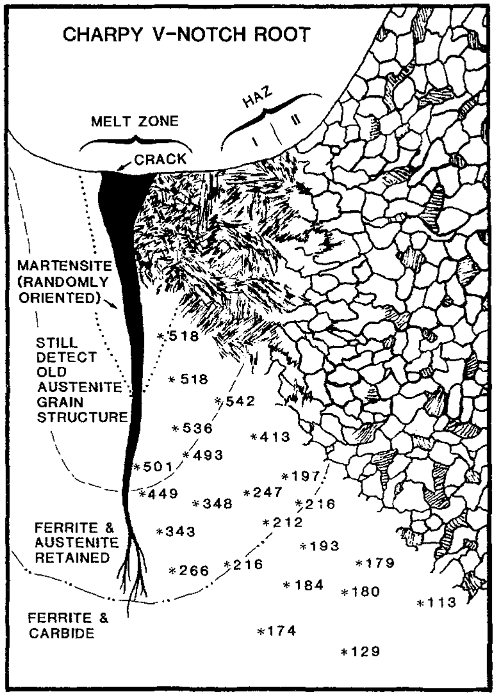

Figure 1 Schematic profile of a metallographic profile of the laser-glazed region of Charpy V-notch fracture sample and microhardness results.

is from austenite to the bulk structure, pearlite. As in the previous zone boundary, there are several grains that reveal a dual structure with a very distinct interface zone between pearlite structures and the austenite phase. There was no indication of a dark etch band between HAZ II and the bulk material as reported for other low-carbon steels [15].

Microhardness measurements were taken in the three regions. Both of the martensite regions yielded relatively uniform high hardness values (≃ 500 DPH). The region of retained austenite and ferrite (HAZ II) gave much lower hardness reading (≃ 350 to 400 DPH). Bulk material again gave a much lower reading (≃ 200 DPH) (Fig. 1).

4.2. Crack initiation

Originally, the purpose of the V-notch in a Charpy sample was to introduce into a narrow region a stress concentration rise. This point is made more emphatic by the introduction of fatigue precracking to Charpy samples. With the laser-glazed samples, as the three-point bend test progresses, the root of the glazed V-notch region becomes highly stressed. As the stress level continues to increase, the laser-glazed material eventually reaches its fracture toughness limit and starts to crack, rapidly propagating an atomic size, plane strain, crack through the laser-glazed material and into the Charpy bulk material. This phenomenon is precisely the objective of fatigue precracking that the ASTM requires in K_{IC} evaluations as described in ASTM E-399.

A study of fatigue crack front shape and its effect on fracture toughness measurements has recently shown that, in addition to the difficulty of meeting the shape on profile criteria for K_{IC}, the results of some samples that do meet the current criteria provide questionable results [19]. The uniformity of the laser weld depth could easily eliminate misshaping due to fatigue cracking and provide more meaningful results for standard and nonstandard size samples.

In Fig. 3a, a scanning electron microscope photograph of the fracture surface indicates the

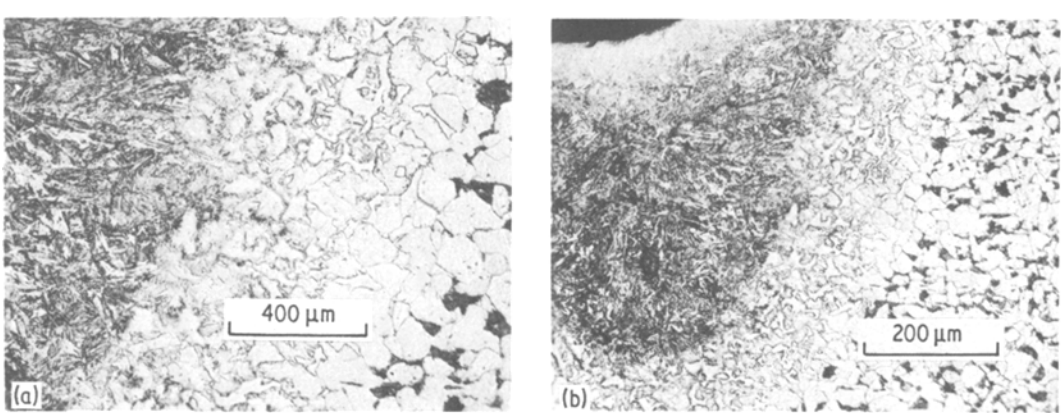

Figure 2 Metallographic profile of laser-glazed V-notch root, three distinct regions: (i) fibre martensite in laser melted zone; (ii) heat affect zone; and (iii) unaffected bulk material.

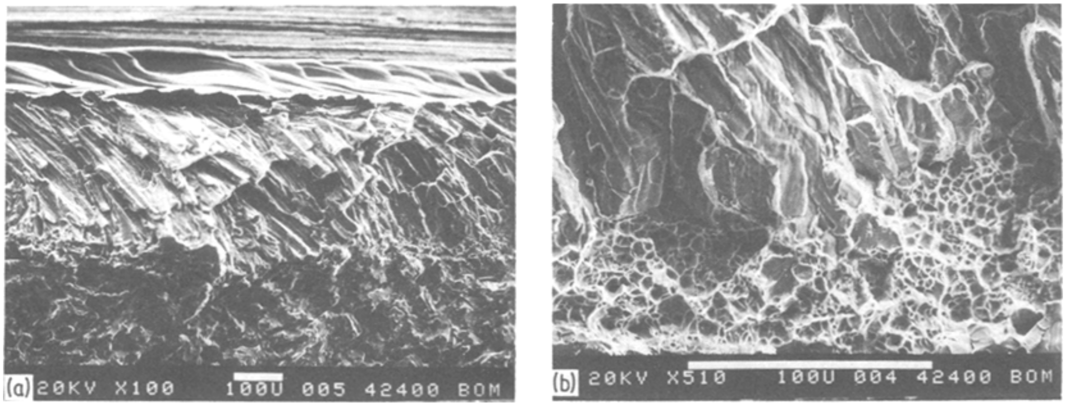

Figure 3 Scanning electron microscopic examination of fracture surface (a) overall fracture profile from top of V-notch through to bulk metal, and (b) ductile to brittle transition zone, note sharp transition region.

depth of the vapour melt, the sharp, brittle nature of the surface crack initiating from the root of the V-notch, the abrupt transition from brittle, laser-glazed region into ductile bulk material, and most importantly, the uniformity of interface profile between the brittle and ductile fracture regions. Fig. 3b is an enlargement of the previous photograph and the sharp transition from brittle to ductile phase is clearly demonstrated. Direction of fracture and structure of the brittle failure surface provide evidence supporting the frequently observed columnar growth of grains in the laser melt zone [15].

4.3. Fracture values

From the three-point bend, instrumented drop-weight, impact test results two different analyses of the data were conducted: fracture toughness (K), and normalized failure energy (Table I). The (a/W) ratio, crack depth to sample width, and the fracture area were determined from the samples after testing. Fatigue (a/W) data were obtained by the optical microscopic determination of the fatigue–fracture interface. Laser-glazed (a/W) data were obtained by the optical microscopic determination of the sharp interface shown in Fig. 3b. For the laser-glazed samples, the crack profile depth was extremely uniform across the entire V-notch width and well within the criteria for fracture toughness samples.

Fracture data from impact testing indicate laser-glazed samples and precracked V-notch samples have nearly identical failure values. Fracture toughness values are remarkably similar at lower temperatures. And, considering the differences in (a/W) ratios between laser-glazed and precracked samples, the fracture toughness values at high temperatures are also quite similar for both AISI 1018 and 1040 steels.

Failure energies, when corrected for fracture areas, are very similar for the laser-glazed and for the precracked V-notch samples at lower temperatures (Fig. 4). Both brittle and transition regions of the Charpy V-notch failure energy curve against temperature for laser-glazed and precracked samples are identical.

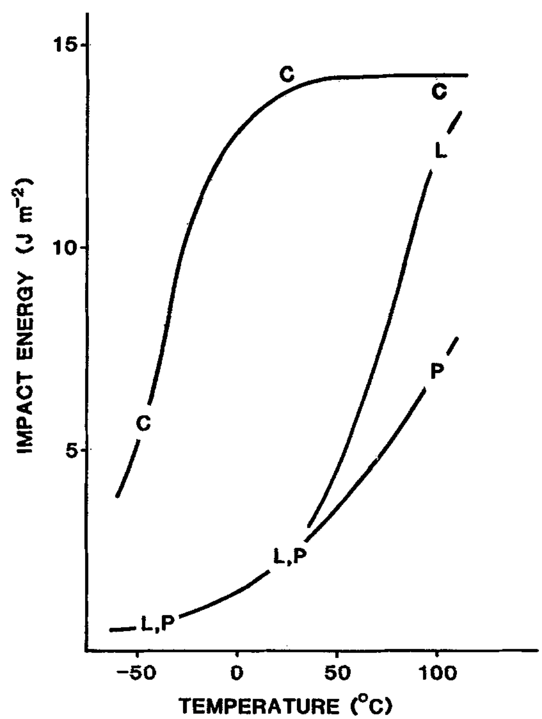

Figure 4 Charpy V-notch fracture energy against test temperature for AISI 1040 samples: C–Charpy V-notch, L–Laser-glazed, P–Precracked.

Differences in fracture results between laser-glazed and precracked samples are believed to be attributed to the (a/W) ratio and could be corrected by using similar crack geometries [20].

5. Conclusions

Laser-glazed, low carbon steel Charpy samples have fracture properties similar to fatigue, pre-cracked, V-notch samples at lower failure energies.

Laser-glazing produces a high strength region composed of two areas: martensite and retained austenite, and ferrite.

During fracture testing, stressing of laser-glazed samples results in the introduction of a crack of atomic size and uniform depth into the bulk material. Thus, the ASTM criterion of crack front profile is met. Further testing seems warranted to determine if laser-glazing offers an alternative to fatigue precracking samples for fracture testing.

Results from this study on low carbon alloy steels, suggest that laser-glazing may be applied to fracture samples of other materials or alloys. Possible consequences of laser-glazing are not limited to phase alteration. Alloy, or chemical, alteration of the melt zone can be accomplished by coating the surface before laser-glazing. Alloying elements could be judiciously chosen to produce an embrittled region, which would produce similar results to the structural alteration [22].

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