Fatigue performance and residual stresses in laser treated 50CrV4 steel

J. M. BELLÓ, B. J. FERNÁNDEZ, V. LÓPEZ, J. RUIZ
CENIM (CSIC), Avda. Gregorio del Amo, 8 E-28040, Madrid, Spain

The effects of continuous CO_2 laser surface quenching of one side of a rectangular section of 50CrV4 steel samples are studied. The treatment is carried out in one or several passes, working with a square beam with a uniform power density of 2550 W cm^{-2} at scan rates between 700 and 1400 mm min^{-1}, with either a single or overlapped sweep of the beam. The magnitude and distribution of internal longitudinal stresses created by the uniform treatment of the surface, relating them to the harness gradients created in depth, conditioned by structural variations, are considered. The uniform treatment of the surface leads to considerable improvement in fatigue performance. In the presence of the thermally affected zones produced by successive sweeps of the beam, however, the noted improvement is largely lost.

1. Introduction

The main aim of surface quenching of steel pieces is local surface hardening, and thus improved wear performance. Due to the treatment, compression stresses appear near the treated surface, creating favourable conditions to withstand higher cyclical loads during service. Surface quenching of the product may be achieved by induction or laser treatment [1, 2]. Surface heating by laser treatment is extremely fast and, as a result, a secondary quenching medium is not required to turn the austenitized layer of the steel into martensite. The material surrounding the thin irradiated zone acts as a powerful quenching medium.

The present study analyses the effect of laser surface quenching on 50CrV4 steel; this steel is often used for springs that are to be subjected to fatigue conditions in service. The test samples allowed the simultaneous monitoring of structural and hardness variations caused by the treatment; also, determination of the distribution of internal stresses created and the effect on fatigue behaviour under one way bending was allowed. The laser treatment is carried out using single or multiple passes to consider the effect of the treatment on material affected by previous passes.

2. Material and methods

The composition of the 50CrV4 steel used is shown in Table I.

The test samples were machined from a 25 × 12 mm bar, vacuum quenched in oil from 860 °C and tempered at 620 °C. After quenching, the hardness attained a value of 640, HV = 1. Following tempering, the hardness was 315, HV = 1. The surface to be laser treated was spray covered with matte black paint.

TABLE I Composition of 50CrV4 steel (wt %)

C	Mn	Si	P	S	Cr	V
0.48	0.83	0.26	0.008	0.010	1.1	0.17

Laser treatment of the samples was performed using a 5 kW Spectra Physics laser equipment, Mod. 975 CO_2. The resonant cavity supplied a multimodal type of beam. An optical integrator was used to obtain a square beam with uniform internal energy distribution.

3. Experimental procedure

Surface laser treatments were carried out using a 5 kW output square beam, 15 × 15 mm. The velocities were 700, 900, 1200 and 1400 mm min^{-1}, corresponding to beam interaction times of 1.2, 0.93, 0.70 and 0.60 s, respectively. The square beam, with a power density of 2250 W cm^{-2}, was larger than the 11.5 mm wide test sample. Treatment surfaces are estimated to absorb 65% of the radiation emitted [3]. The effects of these treatments were studied by metallographic observation, Vickers determination of hardness, internal stress measurement and fatigue testing. Samples of 73 × 17 × 11.5 mm were used for the determination of internal stresses. The treatment was carried out, moving the sample longitudinally so that the beam illuminated the treatment surface, of 73 × 11.5 mm, uninterruptedly from one extreme to the other at the wanted beam velocity.

The changes of curvature in the sample were measured as successive thin layers; these were removed to determine the value of longitudinal stresses at different depths. For this purpose the sample was marked prior to experimentation at three points on the two 73 × 17 mm lateral faces, at a distance of approximately 2 mm from the treated surface. Two of the marks were made near the ends of the sample and the third one was placed approximately in the centre.

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After initial measurement, the first longitudinal cut was made at 9 mm from the treated surface (Fig. 1a), followed by electrolytic dissolution to eliminate the layer affected by machining stresses. The subsequent thin layers (0.3–0.4 mm) were eliminated by electrolytic dissolution using a 1 M sulphuric acid bath at room temperature, where a continuous current of 3.5 A was applied.

After eliminating each successive layer of material, the co-ordinates of the reference points were determined anew to evaluate the changes of curvature, and thus simplify the calculation of residual stresses.

On removing layers with internal stresses, the specimen is elastically deformed until reaching a new equilibrium state. The curvature change, measured by means of the co-ordinates of the three marks, can be related to the value of the stress lodged in the removed layer.

Fig. 1b and 1c shows the aspect of the sample in successive stages of the attack process. Spectacular curvature was acquired by the sample in final stage because of the high tension gradients in the affected area. Dissolution was initially carried out on the face opposite to the treated surface, with several measurements taken until the height of the sample approached the reference marks. At this point the sample was extremely flexible, and clearly showed the effects of the removal of thin layers of the treated zone.

Samples of $150 \times 17 \times 11.5$ mm were used for the bend test. This fatigue test was carried out on a 810 Material Test System machine, operating with a minimum load of 5000 N and a maximum load of up to 40 000 N. Fig. 2 shows the sample mounted on the testing device. The laser treated surface is in the lower part of the sample. The loads were applied at a frequency of 5 cycles s^{-1}. The distance between the lower cylindrical supports is 67.5 mm.

These fatigue tests were conducted with three groups of samples: those previously only subjected to quenching and tempering, those subsequently laser treated at a scan rate of 1200 mm min^{-1} over the whole of 11.5 mm wide face, and finally those that after uniform treatment were again subjected to the action of the beam as shown in Fig. 3. Here, two supplementary passes were carried out across the central zone of the treated surface. This supplementary treatment created an overlapping zone.

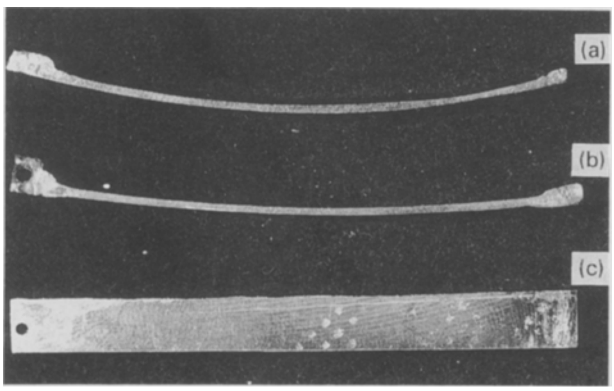

Figure 1 Aspect of a sample after elimination of successive layers parallel to the treated surface.

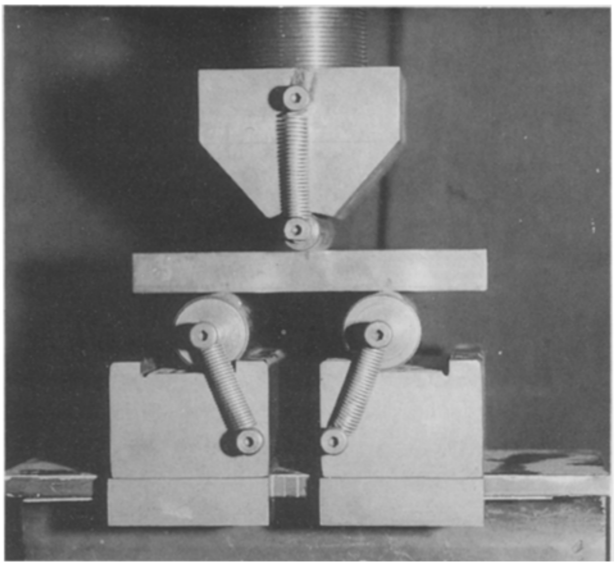

Figure 2 MTS machine for one way bending tests.

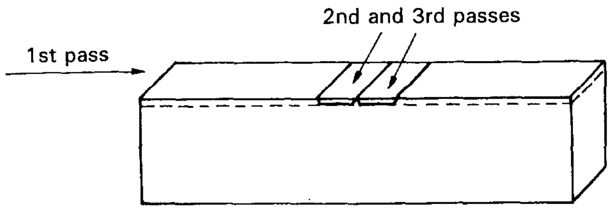

Figure 3 Treatment with two additional transverse passes, after the uniform longitudinal pass.

4. Results and discussion

4.1. Laser surface hardening with single longitudinal pass

Working with single passes, the depth of hardening is slightly smaller in the centre than on the edges of the treated surface. This difference could arise because the laser beam, larger than the 11.5 mm wide sample, illuminates over the edges supplying additional calorific energy to the zone.

The steel shows a fully martensitic structure below the surface (Fig. 4a). At the bottom of the heat affected zone (Fig. 4b), the steel microstructure shows the pronounced effect of additional tempering. At a greater depth, in the area not affected by laser treatment, the structure is that of the material tempered at high temperature (Fig. 4c), showing fine carbides in a ferritic matrix.

The hardening profile varies as a function of the process variables (Fig. 5).

The fully martensitic zone attains a hardness of 700, HV = 0.5. The depth of this totally quenched layer decreases as the speed of the sample increases. For a displacement speed of 1400 mm min^{-1}, the 700, HV = 0.5 hardness is not even attained on the surface.

The hardness profiles have a minimum, corresponding to the depth where the material reached a temperature beyond the value of the previous tempering temperature. Beyond this area of additional

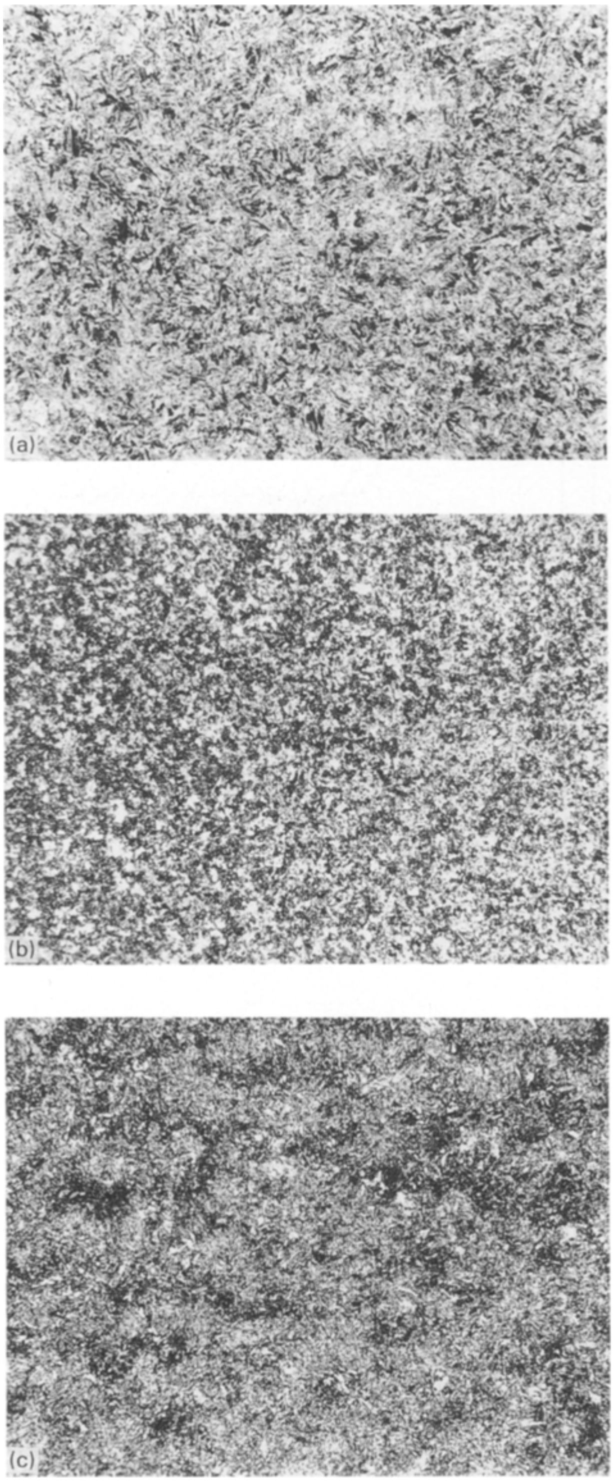

Figure 4 Microstructure of 50CrV4 steel in different zones of a laser treated sample: (a) fully martensitic structure near to the surface, (b) supplementary tempering zone below the martensitic layer, (c) non heat affected zone (× 500).

tempering, the hardness of the material is maintained at the initial value of 333, HV = 0.5.

The effect of laser treatment on the internal stresses is shown in Fig. 6; which sets out the values of longitudinal internal stresses as a function of depth for different displacement speeds.

All the stress diagrams present a compression loaded surface layer, followed by a heavily tension loaded zone. Beyond these two layers the absolute values of the stresses remain relatively low.

It was found that the lower the speed of the pass, the greater the thickness of the zone heavily affected by internal stresses. The fully or partially quenched layer is compression loaded, with stresses ranging from 250 to 400 MPa. Tension stresses from 370 to 650 MPa are found beneath the quenched layer. The order of magnitude of the measured internal stresses is similar to that obtained by other authors on laser treated SAE 52100 and SAE 1045 steels [2].

A close coincidence is noted between the internal stress distribution and the structural changes produced during the quenching process. The data in Fig. 6 allow estimation of the depths at which the change of sign of the stresses, from compression to traction, for each scan rate occur. On the other hand, the C-marked profiles of Fig. 5, corresponding to the central zone of the sample, allow evaluation of the depths in which the harness begins to rise. A coincidence is found between the distance to the surface, corresponding to the change of sign of the stresses, and the depth where martensitic quenching begins to appear. This agrees with results obtained by other researchers [4, 5], and confirms that the changes of volume produced during quenching are those that generate heavy surface compression stresses.

4.2. Surface treatment with supplementary transverse passes

The macrograph shown in Fig. 7 corresponds to a longitudinal cross-section of a sample treated with two additional transverse passes that caused the two tracks that can be appreciated. A speed of 1200 mm min^{-1} was used for both the first longitudinal pass and the two transverse passes.

Fig. 8 is a macrograph of the central zone of the treated surface. It shows one of the tracks created by the transverse pass and part of the adjoining track. Fig. 9 represents the hardness profile of this surface. Letters A to G correspond to the points indicated in Fig. 8.

In the A–B zone the hardness, 705, HV = 1, corresponds to the first longitudinal pass of the beam. In the C–D and F–G zones, corresponding to the two transverse passes, a higher hardness value of 755 HV = 1 is reached having obtained a harder martensite than the first pass due to additional treatment. The laser beam transverse pass causes a tempering effect on the B–C zone next to the edge of the track. A double sided tempering effect appears in zone D–F. A similar effect is observed working with overlap zones [6]. Fig. 10 shows the hardness profiles corresponding to three characteristic zones of the longitudinal section of the sample. The profile indicated by P belongs to the zone affected exclusively by the first longitudinal pass. The profile designated by S corresponds to the centre of the zone treated with a second transverse pass. The depth of hardening is considerably greater due to the prior state created in the material by the first pass [7]. In the zone between the two transverse tracks (profile T) the tempering produced by the thermal effect of the transverse passes reduces the hardness obtained with the quenching by the first pass.

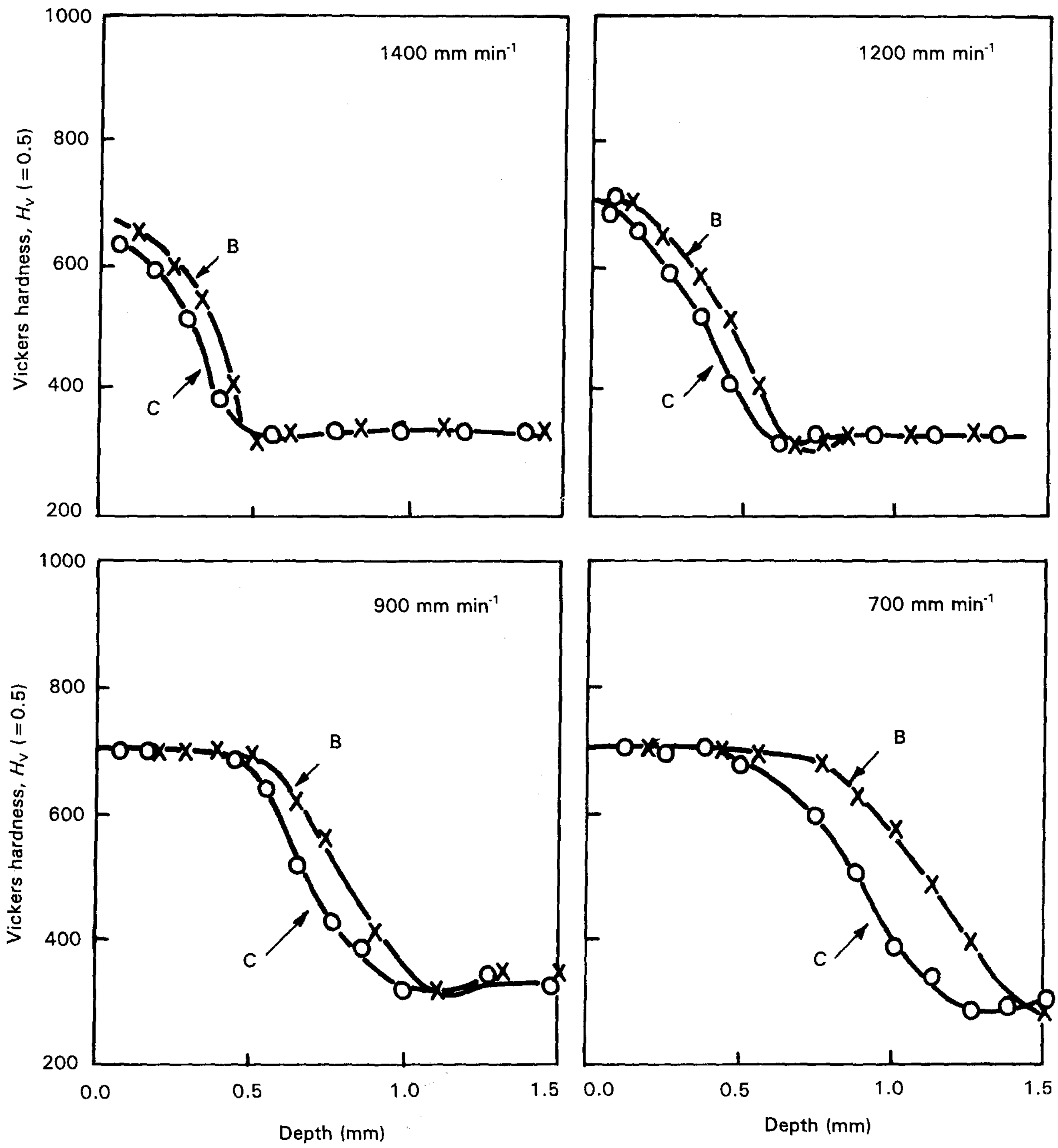

Figure 5 Hardness profiles for 5 kW output power and four different scan rates. (C) centre, (B) 1 mm from edge.

4.3. Fatigue tests

Fig. 11 indicates the results obtained by the bending fatigue tests. The lower line, marked C, corresponds to experiments with quenched and tempered samples without laser treatment, in which loads of 25 000 N for 3.10^6 cycles are supported without breakage. After the single pass laser surface treatment performed at a 1200 mm min^{-1} scan rate, line A, the fatigue threshold increases by 40% to around 35 000 N s^{-1}. This fatigue resistance improvement agrees with the result obtained for a non-alloyed SAE 1045 steel by Singh *et al.* [8]. As a comparison, Ericcson and Lin [5], working with a notched fatigue specimen of SS 2244 steel, found that the fatigue limit increased to 69%. Improvement of the fatigue properties could be explained by surface hardening and compressive stress.

Consequently, of the two additional transverse passes, line B, the fatigue threshold increases 8% to a value of 27 000 N.

Fig. 12 shows the effect of laser treatment on the location of the fracture origin in the fatigue samples. For the quenched and tempered samples without laser treatment (Fig. 12a), fracture begins in a corner of the treated surface, which supports the maximum fatigue load. Propagation of the crack creates an irregular front, due to the appearance of another origin in the opposite corner. When both marks meet, steps appear on the breakage surface. Fig. 12b shows a fractograph of a sample, tested after single pass surface laser treatment. In this case the origin lies 0.9 mm beneath the corner. Fracture commences in the zone where the bend load is added to the maximum internal tension

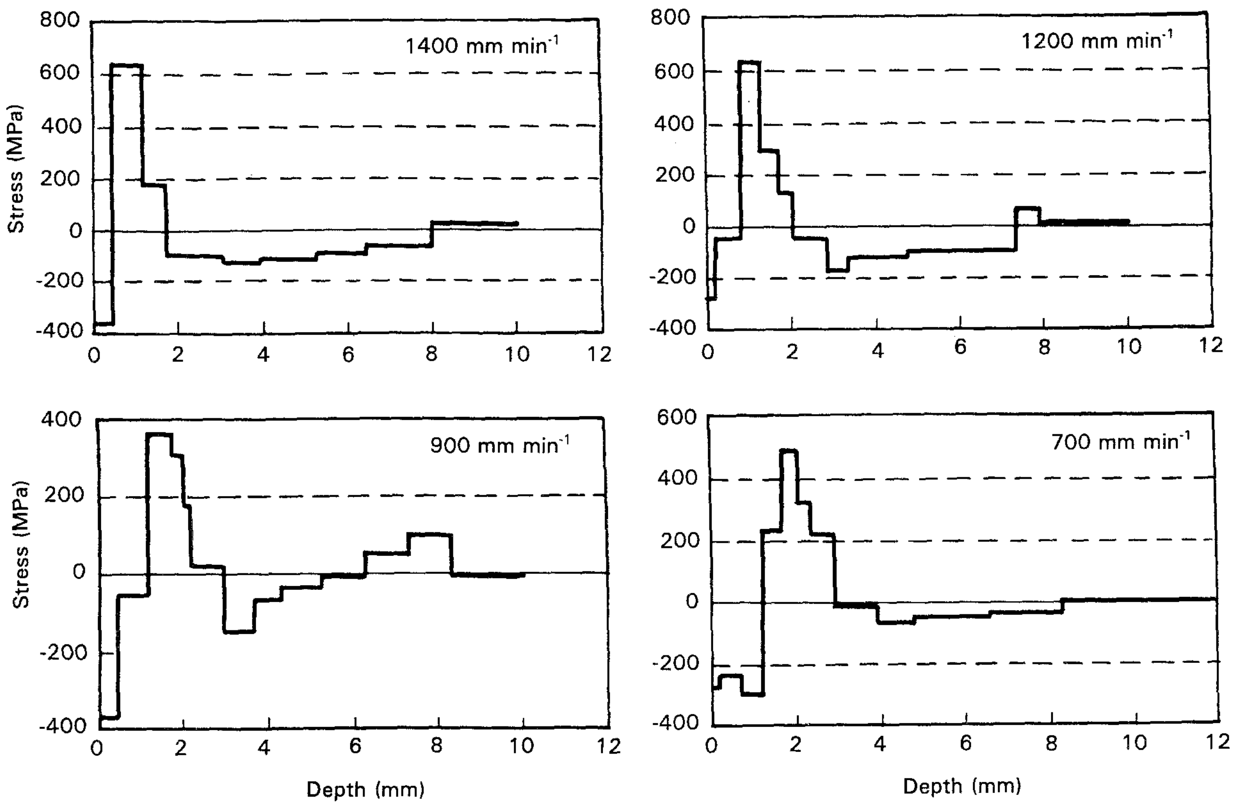

Figure 6 Internal stresses measured in samples treated with 5 kW output power for four different scan rates.

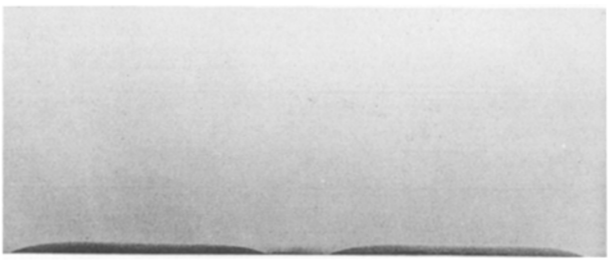

Figure 7 Macrograph of a longitudinal cross-section of the sample showing the effect of transverse laser passes (× 2.2).

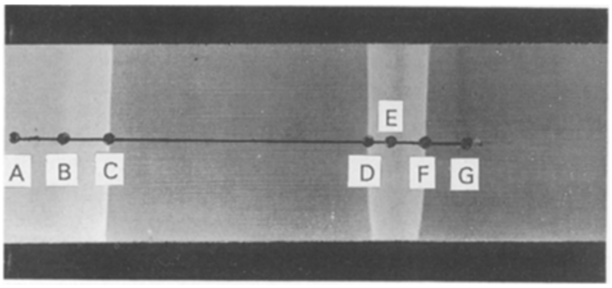

Figure 8 Macrograph of the sample surface in the zone (A–G) of transverse laser passes (× 2.2).

stresses. Once begun, it propagates continuously over the laser hardened layer and through the underlying material. In overlaid transverse laser passes (Fig. 12c), multiple origins appear in the central part of the treated surface. Regardless of the type of treatment, the fracture surface corresponds to that of a fatigue induced crack (Fig. 12d).

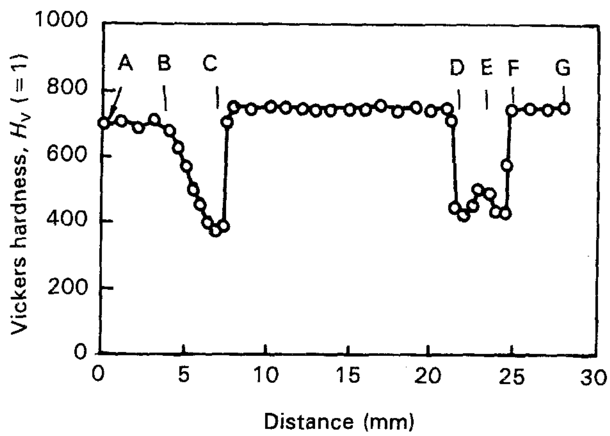

Figure 9 Hardness profile (A–G) of treated surface, following line marked in Fig. 8.

It is clear that uniform laser surface treatment increases the threshold fatigue stress from 250 to 350 MPa. This significant increase ought not to be surprising bearing in mind the internal compression stresses on the treated surface; in this case around 250 MPa (Fig. 6b). However, the pretensioned zone where the crack appears not only withstands this test tension (somewhat less than 350 MPa), but also withstands the additional tension of around 650 MPa implied by the internal stresses in this region. This can only be attributed to the shift of the point at which the crack begins. In the untreated sample, the crack starts at the corner of the sample (Fig. 6a), while the starting point in the treated sample is on the lateral surface of it but considerably separated from the quenched surface itself (0.9 mm), even below the quench hardened

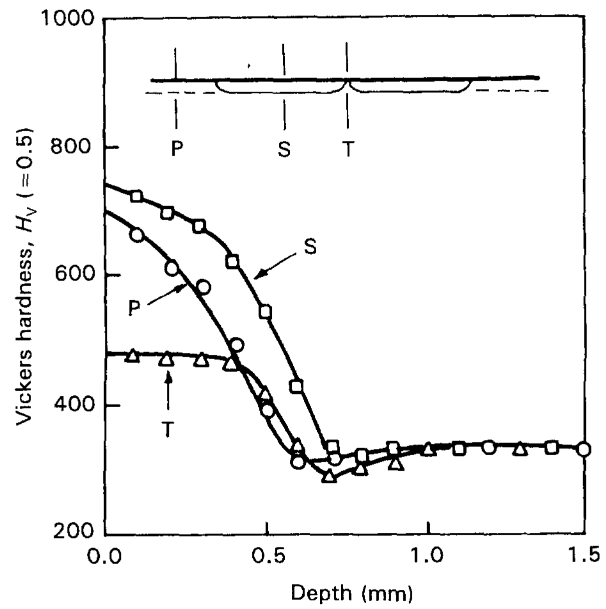

Figure 10 Hardness depth profiles for different transverse sections of the sample in the zone affected by additional passes. (P) zone of first longitudinal pass, (S) zone of record transverse pass, (T) zone between the two transverse passes.

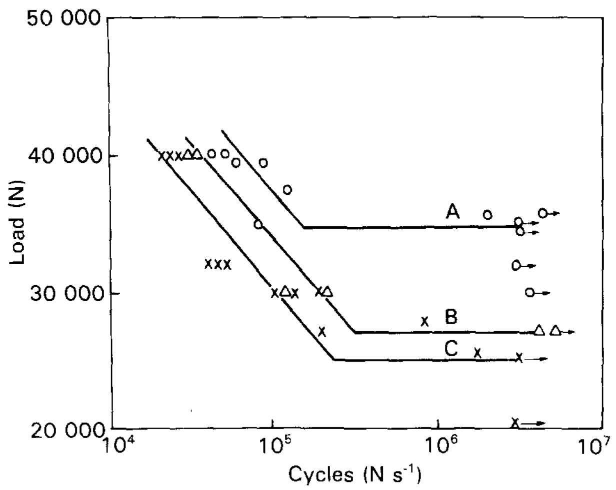

Figure 11 Results of fatigue tests on samples at different treatment stages: (A) single pass laser treated material, (B) laser treatment with two additional transverse passes, (C) reference material (Q&T).

layer or the one affected by supplementary tempering (Fig. 5).

The effect of non-uniform treatment of the surface is attributed to internal stresses that appear in the zones affected thermally by the overlay of beam passes in which tension stresses appear [9].

5. Conclusions

Laser surface quenching of pieces of 50CrV4 steel achieves a martensitic superficial layer of approximately 700, HV = 0.5, with a thickness which varies according to the process variables.

Uniform laser treatment of the surface zone, which is most heavily tension loaded during the bending test, leads to considerable improvement in the fatigue behaviour of the sample. This effect is due to compression stresses arising during transformation of the material and to displacement of the point at which the fatigue crack starts.

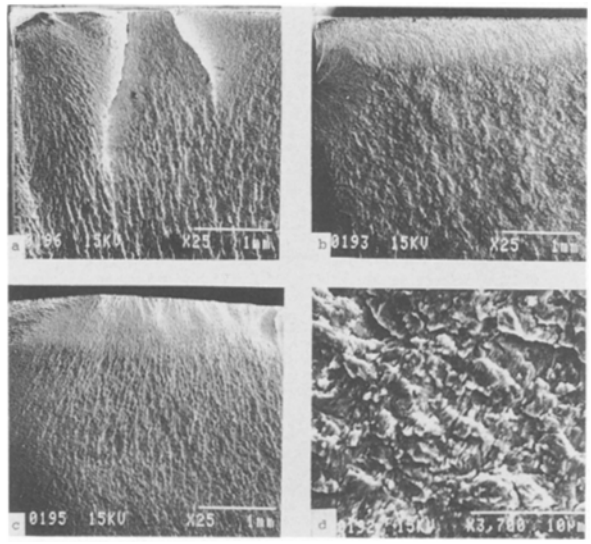

Figure 12 SEM fractographs of samples for different treatments.

According to the internal longitudinal stress profile, the martensitic quench hardened zone shows heavy compression stresses of between 250 and 400 MPa.

The additional beam passes over the sample surface and causes a notable tempering effect beside the boundary of the newly created track. This implies a considerable loss of improvement in fatigue resistance procured by uniform laser treatment.

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