Influence of induction hardening on fretting fatigue behaviour of AISI 1045 steel under two different contact pressures

R. Sadeler*, A. B. Sengül

Department of Mechanical Engineering, Faculty of Engineering, Atatürk University, 25240 ERZURUM, Turkey

Received 10 March 2006; received in revised form 14 June 2006; accepted 21 June 2006

Abstract

Fretting involves contact between surfaces undergoing small cyclic relative tangential motion. The resultant wear and initiation of fatigue cracks are strongly influenced by the nature of the surface. The induction hardening treatment is an established surface hardening treatment, which produces both local hardness and the development of compressive stresses in the surface. The present investigation is designed to assess the effect of the induction hardening treatment on the fretting fatigue behaviour of AISI 1045 steel under two different contact pressures (100 and 200 MPa). The results showed that the plain and fretting fatigue behaviours of induction hardened AISI 1045 steel were improved compared to untreated. However, the effect of contact pressure in the range of the present study was not significant for both untreated and induction hardened specimens.

Key words: fatigue, fretting fatigue, induction hardening

1. Introduction

Fretting is the oscillatory tangential relative movement between two contacting surfaces arising from vibration or cyclic stressing of one of the components, and is typically of very small amplitude, usually less than 30 μm. It results in removal of material by a wear process, but more seriously, from the engineering point of view, it is the cause of early initiation of fatigue cracks.

It has been reported that up to 50 variables might influence the magnitude and rate of fretting process [1]. Contact pressure in addition to coefficient of friction and magnitude of slip are also considered to be one of the most important factors that control fretting fatigue. Many studies have shown that fretting fatigue life decreased with an increase in contact pressure [2–4]. However, a few studies have shown that the fretting fatigue life exhibited a minimum at a certain contact pressure [5–7].

Since fretting fatigue is a surface related phenomenon, engineering the surface to produce a hard and wear resistant layer is believed to be an effective palliative. Attempts have been made in the past to modify the contact surfaces so as to improve the fretting fatigue strength of materials. There are many surface modification methods used to mitigate fretting damage [8–11]. The nature and condition of the surfaces are important factors in their susceptibility to fretting damage [12]. Among the various surface engineering techniques available, induction hardened low-alloyed medium carbon steels are widely used to increase the plain fatigue and tribological properties for critical automotive and machine applications such as propulsion shafts, crankshafts and steering knuckles. Nevertheless, there have been few papers on the benefits of the application of the induction hardening treatment in the mitigation of the fretting damage under various contact pressures, though the effect of the induction hardening on the plane fatigue has been widely studied [13–15].

The purpose of this study is to investigate the effect of induction hardening treatment on fretting fatigue behaviour of AISI 1045 steel in contact with similar material under two different contact pressures.

2. Experimental details

The material used in this study is a commercial me-

*Corresponding author: tel.: +90-442-2314841, fax: +90-442-2360957, e-mail address: receps@atauni.edu.tr, recepsadeler@yahoo.com

Table 1. Chemical composition of AISI 1045 steel

	Chemical composition (wt.%)							
	C	Si	Mn	P	S	Cr	Mo	Ni
AISI 1045	0.4220	0.2440	0.6070	0.0190	0.0330	0.1970	0.0332	0.1220

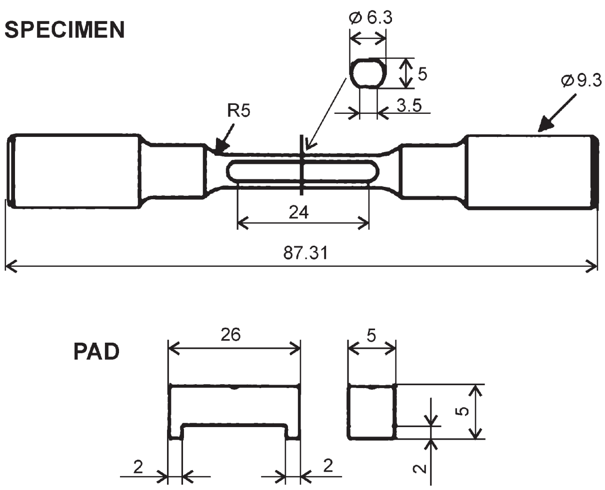

Fig. 1. Schematic drawings of fretting fatigue specimen and fretting pad in milimetres.

dium carbon steel (AISI 1045), which is widely used for gears and shaft manufacturing. Chemical composition of the material is shown in Table 1.

The specimens were machined from AISI 1045 steel rod with 12 mm diameter in the centre of which a gauge part was machined to produce two parallel flats, reducing the thickness to 5 mm, with generous fillet radio (Fig. 1). For plane fatigue tests, the specimens with a gage diameter of 6.3 mm and a gage length of 40 mm, for which other geometrical dimensions were the same as those of fretting fatigue test specimens, were machined. The same material was also used for bridge-type flat pads.

Table 2. Induction hardening parameters

Sample	Frequency (kHz)	Power (kW)	Heating time (s)	Temperature (℃)
AISI 1045	450	20	6	850

The gauge parts of the fretting pads were polished with silicon carbide papers grit 800–1200 and then degreased with acetone. The process conditions for induction surface hardening are shown in Table 2. The water was used as a quenching medium. The quenching was applied immediately after the power had been turned off. No tempering was applied.

Plane and fretting fatigue testing were carried out at room temperature in a four-point loading rotating bending machine under constant stress amplitude at a rotational speed of 4000 rpm. The fretting device consists of a pair of bridges of the same material clamped

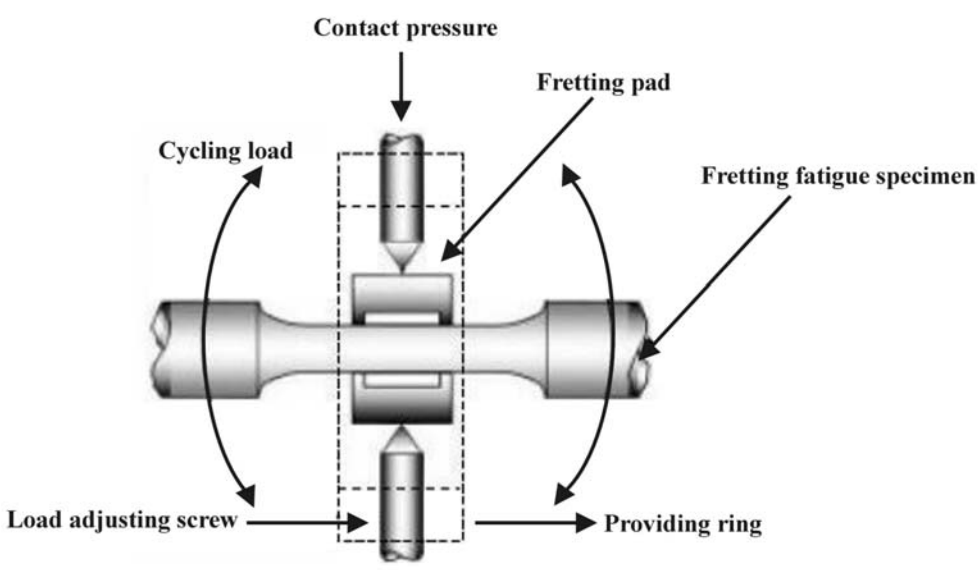

Fig. 2. Schematic drawing of the fretting fatigue testing system in a rotating bending machine.

to the flats with proving ring. By adjusting screw with a torque driver, the normal contact load between the contact pads and the specimen was controlled. The contact pressures used were 100 and 200 MPa. The fretting fatigue testing system used in this study is schematically shown in Fig. 2.

The fatigue limit was defined by the stress at which the specimen survived up to $3 \cdot 10^6$ cycles for all samples considered. Fatigue limit was determined based on the standard JSME S002 with staircase method. According to the standard's recommendation, fatigue limit can be calculated with 6 specimens for 50 % probability of failure. After induction hardening treatment, the representative samples were examined by a series of material characterization techniques, including metallographic examination and microhardness tests. The Vickers microhardness on the cross-section of induction hardened samples was measured, using a PC controlled Buehler–Omnimet tester.

3. Results and discussion

3.1. The distribution of microhardness induced by induction hardening

The Vickers microhardness of base metal samples was measured to be about HV 200. The hardness distribution on the cross-section of the hardened specimen is shown in Fig. 3.

The hardness at the surface of hardened specimen was HV 708 and the maximum hardness was approximately HV 726 at 0.06 mm from the surface. The reason for that the position of maximum hardness is located in surface is the formation of incomplete quenching level during cooling from high temperature. The occurrence of non-martensite is the main reason for the formation of hardness gradient. It is also important to distinguish between total case depth and effective case depth (ECD). In most cases, depth of effective case is approximately 65% of total case depth. According to this definition, the ECD was 1.6 mm, the hardened ratio (HR), which is the ratio of ECD and the radii of the specimen, was 0.64.

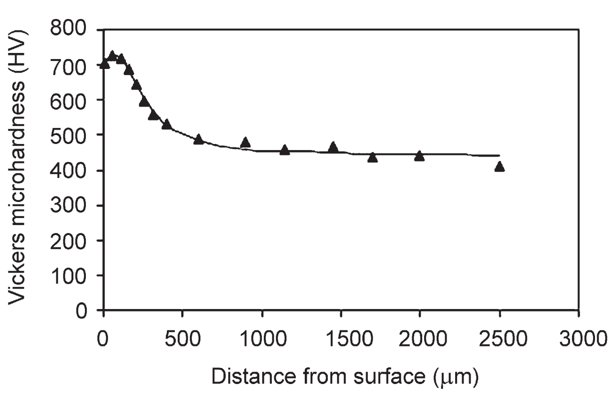

Fig. 3. Relationship between hardness and distance from fretting surface.

3.2. Plain and fretting fatigue characteristic by induction hardening

Figure 4 contains the plain and fretting fatigue test data for untreated and induction hardened samples. These curves demonstrate that the fatigue life is dependent on the level of the applied alternating stress and increases as the applied alternating stress decreases until the fatigue limit is reached, below which failure did not occur. This value of the fatigue limit in this work was defined as $3 \cdot 10^6$. In case of the untreated material the fatigue limit was 332 MPa. It can be also seen from Fig. 4 that the induction hardening treatment results in a significant improvement in the plain fatigue limit compared to untreated material. The plain fatigue limit was improved to approximately 431 MPa for induction hardened specimens. Such improvement was expected because the induction hardening treatment is known to increase the surface hardness and to introduce compressive residual stress in steel. Both factors are beneficial in increasing the resistance to fatigue crack initiation and propagation. The surface hardness of the induction hardened specimens increased significantly as shown in Fig. 3. However, no attempt was made to measure compressive residual stress in this study. There are sufficient evidences from other work that the compressive residual stress is induced by the induction heat treatment, the level of which is as high as the yield strength of the base metal [13].

It is shown that crack initiation in plain fatigue accounts for a large portion of the fatigue life and occurs through the movement of dislocation in the surface region by cyclic shear stress. Increasing the strength of the surface region makes dislocation motion more difficult, thus crack initiation delays and fatigue improves. It is also expected that the presence of a compressive residual stress in the induction hardened samples will result in the maximum resultant alternating stress being moved from the immediate surface to the interfacial region between the case and core [16]. Thus, the resultant stress levels will be lower in the near surface regions than the nominal applied alternating stress.

The effect of fretting on fatigue life of the untreated and induction hardened specimens can be seen in Fig. 4. It is apparent that fretting has a deleterious effect on the fatigue life. In the untreated specimens, fretting damage decreased the fatigue limit from 332 MPa to 282 MPa, and the fatigue life except for higher

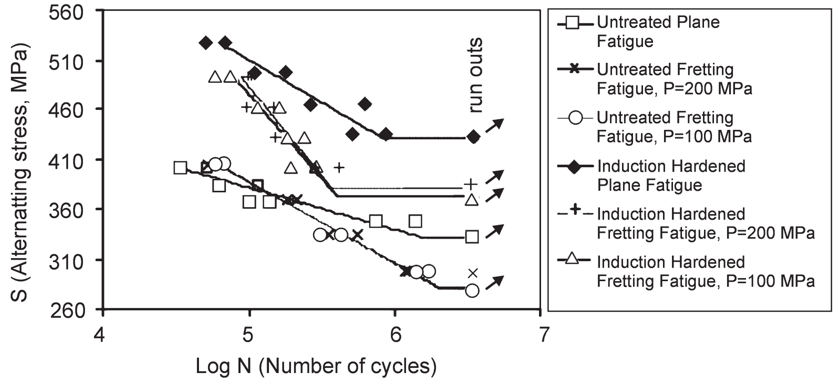

Fig. 4. S-N curves obtained from plain fatigue tests and fretting fatigue tests of AISI 1045 steel.

stress level was drastically reduced. The fretting fatigue limit of the untreated specimens subjected to fretting damage at a contact pressure of 100 MPa was almost identical to that at a contact pressure of 200 MPa. In another word, the contact pressure, which was higher than 100 MPa, did not influence the fretting life. This means that at a contact pressure of 200 MPa, the compensation by two factors will take place: one is acceleration of crack growth due to increase in contact pressure (that is tangential force) and other is deceleration of crack growth by crack closure due to an increase in contact pressure.

The benefit of induction hardening on fatigue strength is also clearly indicated in Fig. 4. Similar to the case of the untreated condition, the fretting damage reduced the fatigue limit from 431 to 373 MPa at a contact pressure of 100 MPa and to 380 MPa at a contact pressure of 200 MPa for the induction hardened specimens. At all stress levels the fretting fatigue lives were considerably lower for both contact pressures compared to the plain fatigue life. In induction hardened specimens, fretting fatigue limits and fretting fatigue lives under contact pressures of 200 MPa and 100 MPa were almost the same. This trend was similar to the case of untreated specimens.

It is suggested that a fretting fatigue crack forms at the region where the frictional shear stress on contact surface locally concentrates. Thus, the decrease in fatigue life by the fretting damage is considered to be due to the decrease in crack initiation life caused by the local stress concentration caused by fretting, and the acceleration of the initial crack propagation by fretting [17]. As one of the main mechanisms of acceleration of initial crack by fretting, the wedge effect where the wear debris goes into the small initial fretting fatigue crack is considered [18]. However, if the crack is fully filled with the wear debris, it is considered that the effect is decreased because the wear debris cannot go into the crack furthermore.

Considering the effect of induction hardening treatment on fretting fatigue life, the main factors to enhance fretting behaviour are residual stress and hardness similar to a case of the plain fatigue. The introduction of compressive residual stress in the surface layer is perhaps one of the most important factors to mitigate unfavourable effect of the fretting fatigue. The compressive residual stress acts as a mean stress and it will reduce the effective stress intensity factor range and prevent crack propagation.

3.3. Morphology of contact area after fretting fatigue

Typical SEM micrographs of the pad contact areas of untreated specimens after the fretting fatigue tests are shown in Fig. 5.

The main crack initiated at the outer edge of the contact region when the contact pressure was low (100 MPa) and the stick region was narrow (see Fig. 5a). However, the main crack initiated not exactly at the edge of the contact region but at a region towards middle portion of the fretted area when the contact pressure was high (200 MPa) and the stick region was wide (see Fig. 5b). Similar observations have been made by Nakazawa et al. [19]. However, it was difficult to resolve the exact location of the stick and slip regions of the scar due to the small size of the slip region and the deposition of oxides on the induction hardened samples.

The schematic drawing of the fretting fatigue crack initiation behaviour is shown in Fig. 6.

The net contact pressure acting in the slip region was probably lower than the average contact pressure due to production and removal of large wear debris. On the other hand, in the stick region, the net contact pressure was probably higher than the average contact pressure due to a decrease in real contact area. Thus, the net frictional stress acting in the stick region was higher, and that in the slip region was lower than the average value. Therefore, stress concentration occurred near the boundaries between the stick and slip regions, and the crack could be easily initiated.

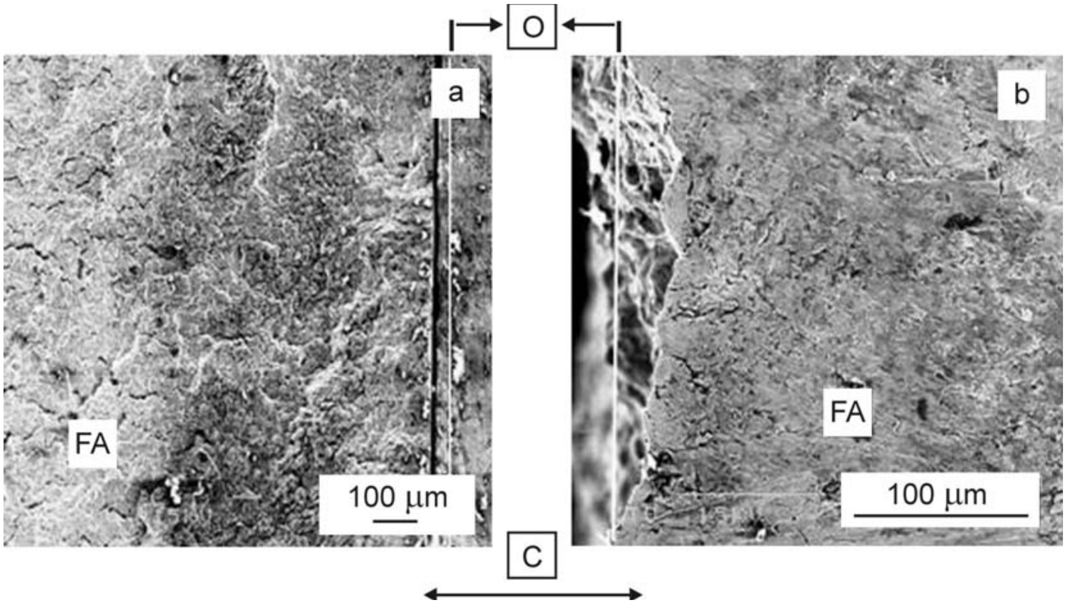

Fig. 5. SEM fractographs of fretted areas of fretting fatigue specimens at (a) untreated at $P = 100$ MPa and (b) untreated at $P = 200$ MPa; FA: Fretted area, O: Outer edges, C: Cyclic load direction.

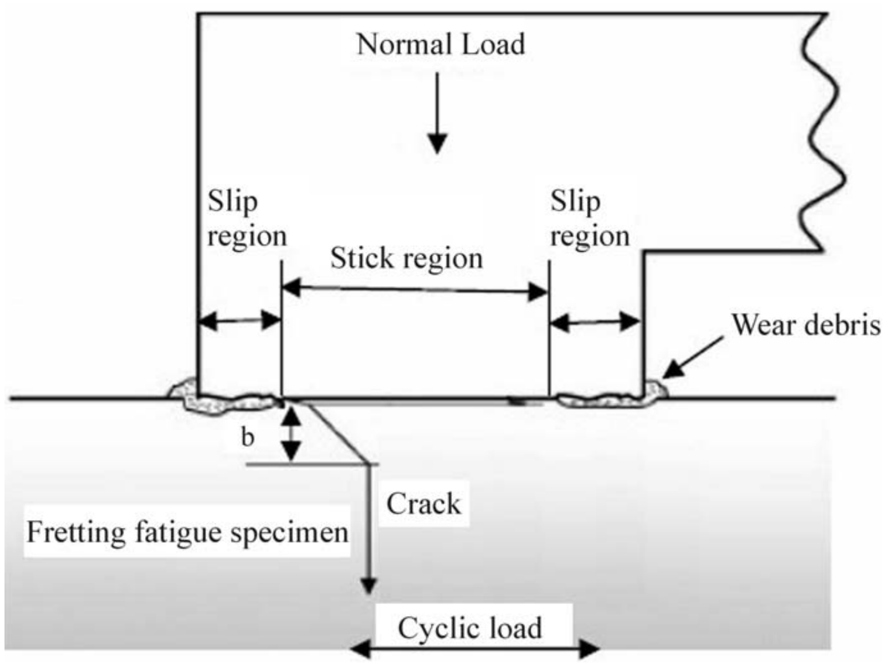

Fig. 6. Schematic drawing of fretting damage; *b*: depth of fracture initiation zone site.

3.4. Plain and fretting fatigue fracture surface morphologies

Typical SEM fractographs near the plain fatigue crack initiation sites of the untreated and induction hardened specimens are shown in Fig. 7. In the untreated samples, the plain fatigue cracks tend to initiate from the surface of the specimen (Fig. 7a), while the plain fatigue crack tends to initiate from the subsurface of the induction hardened specimens (Fig. 7b). However, the defect and inclusion are not recognized near the subsurface crack initiation site. Similar observations have been made by Song et al. [13].

Typical fractographs near the fretting fatigue crack initiation sites of the untreated and induction hardened samples are shown in Fig. 8. The fretting fatigue crack initiates from the surface of specimen. It is clearly observed that multiple microcracks are initiated, particularly for untreated specimens, and after growing to some extent, they link to form a main

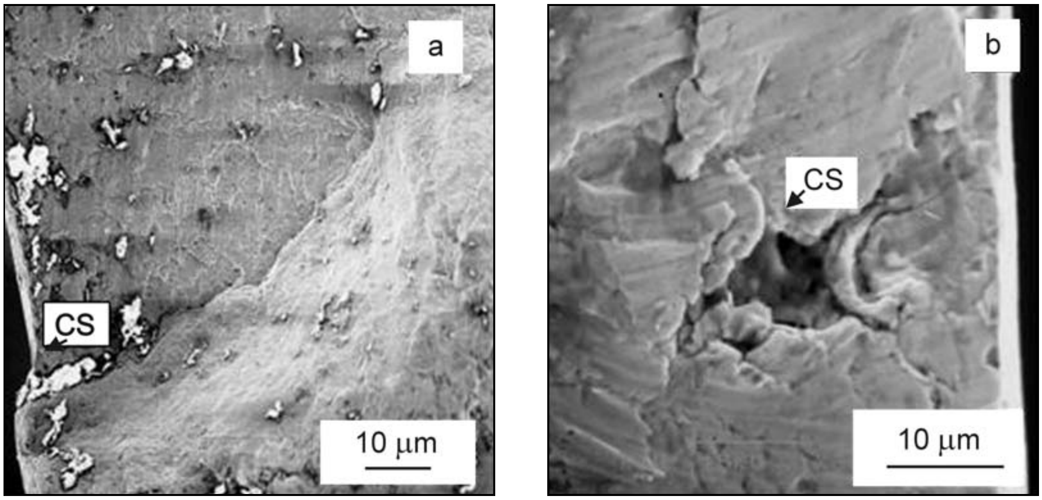

Fig. 7. SEM fractographs of plain fatigue specimens at (a) untreated at σ = 402 MPa and (b) induction hardened at σ = 442 MPa; CS: Crack initiation site.

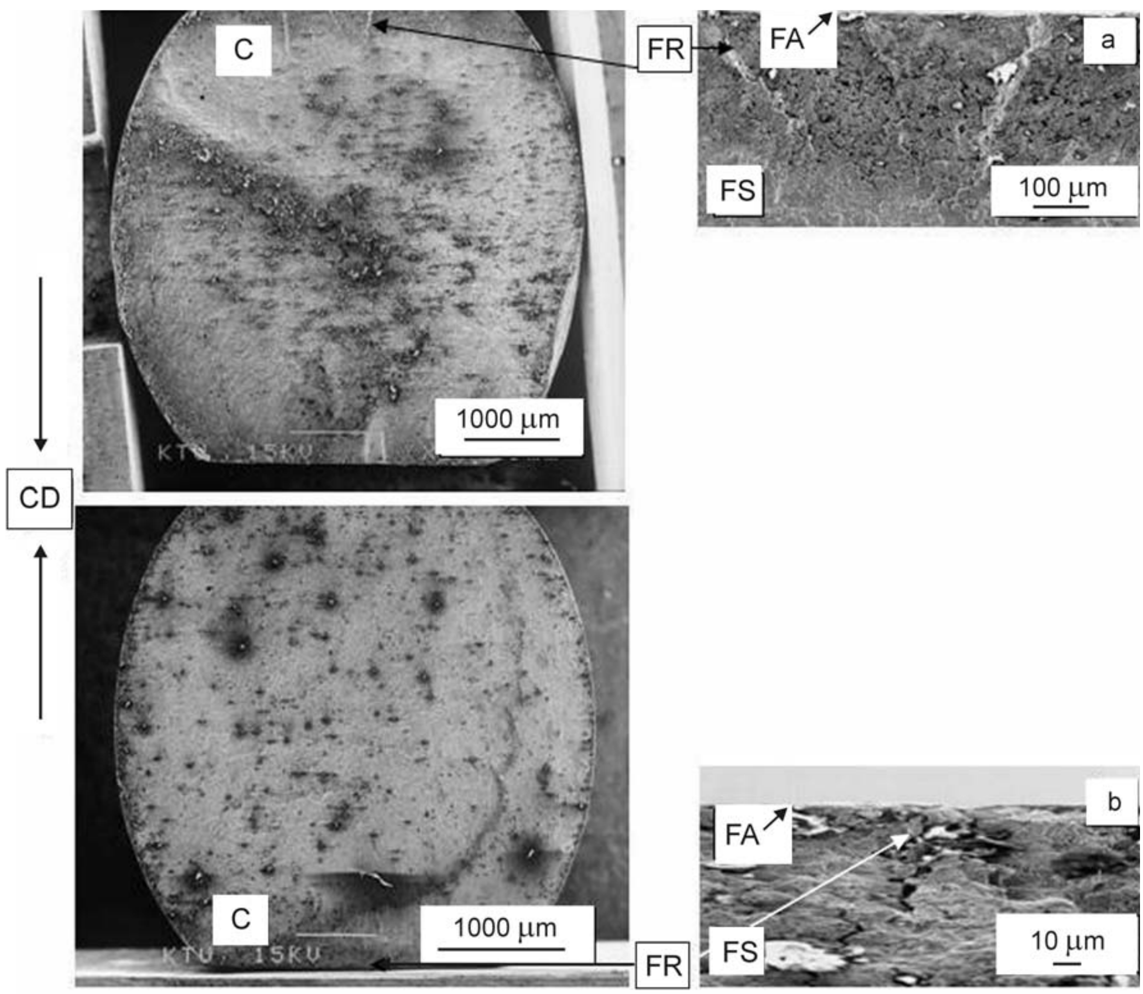

Fig. 8. SEM fractographs of fretting fatigue specimens at (a) untreated at σ = 405 MPa and (b) induction hardened at σ = 387 MPa; FA: Fretted area, FS: Fracture surface, CD: Crack growth direction, C: Crack step, FR: Fracture initiation region.

crack. The crack growth region under influence of the contact pressure is a small region zone on the fracture surface as shown in Fig. 8, which corresponds to region (b) shown in Fig. 6.

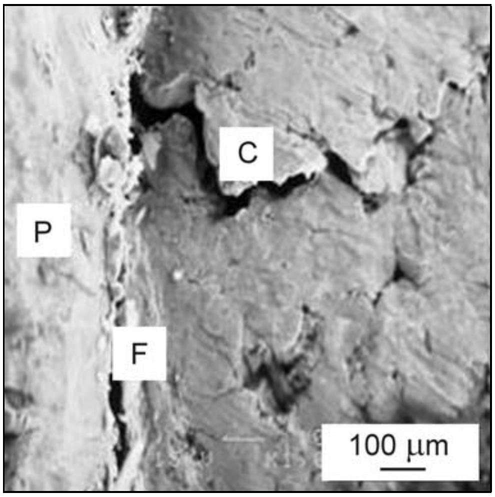

Fig. 9. SEM fractograph of the stick of contact pad to untreated fretting fatigue specimen at a contact pressure of 200 MPa; P: Pad, C: Crack step, F: Fretted surface.

It may be noted that after the test was over, even after releasing the contact load, the pads were sticking to the untreated specimen surface at a contact pressure of 200 MPa. This was not the case in the test carried out at the lower contact pressure of 100 MPa (Fig. 9).

4. Conclusions

Fretting fatigue characteristics of induction hardened AISI 1045 steel, with the same contact material, were investigated under two different contact pressures. The following results were obtained:

1. The fretting significantly reduces the plain fatigue limits of untreated and induction hardened specimens.

2. The plain and fretting fatigue limits were improved by the induction hardening treatment. The improvements resulted from the hardening of the material and the generation of compressive residual stresses in the induction hardened case. The hardened surface caused by the induction hardening treatment increases the resistance to fretting fatigue crack initiation while compressive residual stress in the induction hardened case reduces the crack propagation rate.

3. Fretting fatigue life and limit were almost identical regardless of contact pressure for both untreated and induction hardened specimens. This may be caused by the compensation of two factors: one is the crack growth acceleration due to an increase in contact pressure and the other is the deceleration by crack closure due to an increase in contact pressure.

4. The fretting fatigue cracks for both untreated and induction hardened specimens initiated at the boundary between slip and stick regions at the initial stage of fretting fatigue. After a fretting fatigue crack grows to some depth, it propagates in the same manner as a plain fatigue crack.

Acknowledgements

This work was supported by Atatürk University (Project number 2004/191).

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