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ENVIRONMENTALLY FRIENDLY SURFACE HARDENING OF 4140 STEEL FOR TRIBOLOGICAL APPLICATIONS

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ABSTRACT

One of the most energy intensive industrial and manufacturing processes is the heat treatment of ferrous materials for hardening to improve their friction and wear performance. Examples of surface hardening heat treatments include case carburizing, nitriding, boriding, etc. This paper presents the development of a new energy efficient method to harden steel material as a possible replacement for the current energy intensive heat treatment processes. The new process, friction stir processing (FSP) involves severe plastic deformation of the near surface material by a non-consumable rotating and translating tool. FSP has been demonstrated to locally modify material properties such as ductility, fatigue, fracture toughness, etc. Other potential properties that could be positively affected by FSP are wear and friction properties. In a preliminary study, when applied to 4140 alloy steel, this new FSP process produced adequate hardening of the near surface layer compare to conventional furnace heat hardening of the same alloy. The friction and wear performance of the 4140 hardened by FSP was also observed to be superior than heat hardened surface under dry and lubricated sliding contact.

INTRODUCTION

The vast majority of heat treatments for tribological components such as gears and bearings only require hardening of the surface layer while maintaining softer and higher fracture toughness core. Friction stir processing (FSP), a variant of friction stir welding (FSW), is a new technology that can enhance or modify material properties such as ductility, fatigue life, and fracture toughness in the near surface material [1,2,3]. This method involves severe plastic deformation of the near surface material by a non-consumable rotating and translating tool. The result is a homogenous; almost defect free and refined microstructure. Because grain refinement is a byproduct of the processing, FSP has a great potential as hardening technology.

Advantages of FSP versus conventional heat treatments such as carburizing, nitriding, and laser surface hardening includes: a) it can be localized to an area of interest in large components (by the right selection of tool size and shape we can control the area to be modified); b)energy efficiency (because all the heat used is produced by the tool movement, the energy consumption is minimal); c) no need for quenching, (making the process more environmentally friendly with no hazardous by product); d) faster (processing speed of 5 inches/min compared to several hours in other hardening treatments) and e) safer (especially when compared to other techniques such as laser hardening).

Most of the research on development of FSP has focused on low melting point alloys, such as aluminum, magnesium, and bronze. To date, there is very limited literature toward its application on ferrous materials [4], and its impact on tribological performance is unknown. This study evaluates the effect of FSP in 4140 steel and its ability to improve hardness, friction, and wear properties.

Once fully developed, the new process will provide a highly energy efficient and environmentally friendly means to hardened steel component surfaces with optimized tribological performance.

EXPERIMENTAL DETAILS

4140 steel FSP specimens were processed by Friction Stir Link Inc. with the following processing parameters: 275 RPM rotation speed, traverse speed of 5 inches per minute, 10,000 lbs force and argon atmosphere. In order to compare the tribological performance of FSP specimens with conventionally heat treated ones, rectangular flat from 4140 steel (50x30x6mm) were prepare in four different conditions: the annealed baseline, heat treated (HT) water quenched, HT salt quenched and FSP, all with final surface roughness of 10 nm Ra. Friction and wear tests were conducted with a ball-on-flat contact configuration under unidirectional sliding. 52100 hardened steel balls (Ǿ 0.5”), with surface roughness of 35 nm Ra, were tested against the flat specimens. Two types of test were performed. Dry tests with 5N load (0.54 GPa), and lubricated test with 20N load (0.85 GPa). The lubricant is a basestock PAO4 oil containing no additives and viscosity of 18

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cSt at 40˚C. All tests were run for an hour, at room temperature and with a linear speed of 1cm/s. The friction coefficient was continuously measured during each test, and wear in the test specimens was measured by optical profilometry technique. Worn surfaces were also characterized by both optical microscopy and profilometry to assess wear mechanisms.

RESULTS AND DISCUSSION

The microstructure of the FSP specimens was analyzed by optical and SEM. Metallographic sample of the cross-section areas were prepared by standard techniques: Mounting, polishing and etching in 2% Nital solution. As shown in fig 1, there are three distinctive regions: base material, heat affected zone and processed material within the FSP specimen. The base material consists primarily of a pearlitic and ferrite phases of steel, the processed area consists mainly of martensitic phase, and the transition zone between the processed area and the baseline consists of fine pearlite and banite phases. The microstructural evolution in the processed material results from the severe plastic deformation and the consequent heat generation, in addition to frictional heating of the FSP process. Martensite phase was formed as the temperature in the processed region (~940°C) exceeded the austenitizing temperature of the 4140 steel (≈780˚C), and the cooling rate after the tool passes is fast enough to "quench" the hot austenite phase.

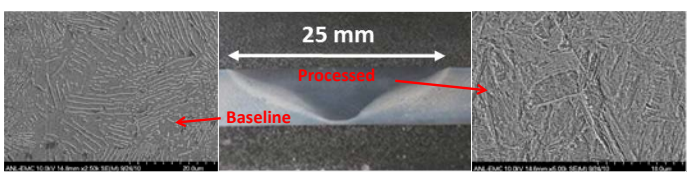

Fig.1:Cross-Section of FSP sample and microstructure of baseline (left) and processed region (right).

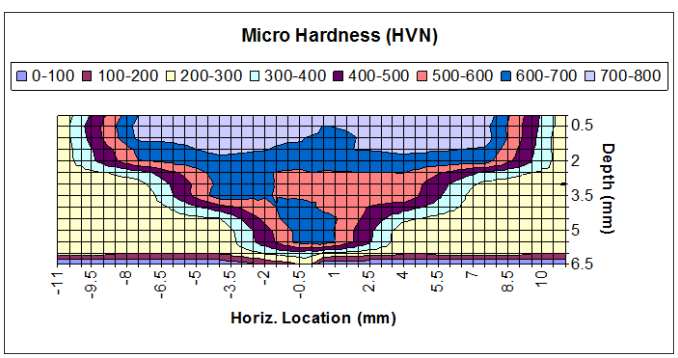

Fig. 2: Hardness Map of FSP and surrounding regions.

Hardness measurements, using a Wilson Tukon micro-hardness Vickers indenter with load of 100g (1N), were conducted over a wide area. Fig. 2 shows the hardness map covering the processed (750 HVN), heat affected and the baseline material (210 HVN). Hardness measurements were also conducted on 4140 materials that were heat treated by conventional methods.

Fig. 3 shows the surface and average hardness of the baseline, heat hardened and FSP treated material. The hardness from FSP is comparable to the conventional heat hardened samples, proving FSP is an effective and rapid method for surface hardening of steel material.

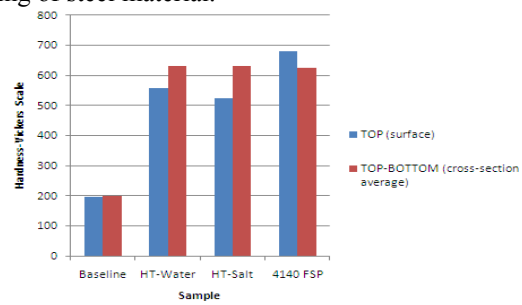

Fig. 3: Hardness plot for the baseline, HT water, HT salt and FSP specimens measured on the surface (blue) and cross section (red).

Friction and wear results are summarized in Fig. 4-5. Friction behavior for the hardened specimens was similar (μ~0.8 dry) and (μ~0.14 lubricated). For the baseline, friction coefficient was lower under dry conditions (μ~0.65), and higher under lubrication (μ~0.2), in good agreement with a softer material undergoing more plastic deformation. As shown in fig 5, wear results varied substantially between different groups. Although all the hardened specimens showed reduced wear compared to the baseline under lubricated contact (reduction by one order of magnitude), under dry contact only significant wear reduction was observed in the FSP sample (25 times less than the baseline and at least an order of magnitude less than conventional heat treated specimens). This improvement in wear behavior can be attributed to microstructural changes in the near surface material consisting of phase transformation and grain refinement.

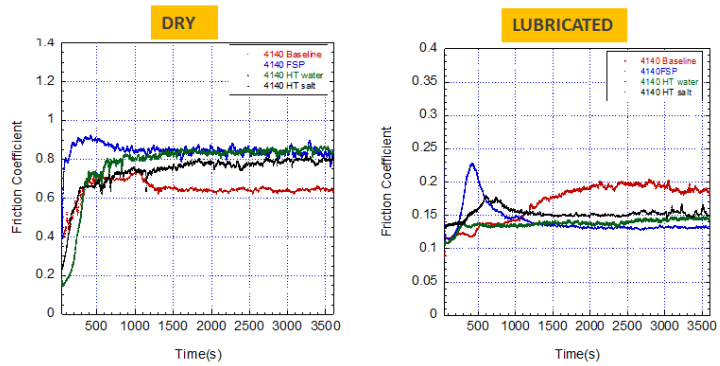

Fig.4: Evolution of friction coefficient for the baseline, HT water, HT salt and FSP specimens tested under dry (left) and lubricated (right) unidirectional sliding contact.

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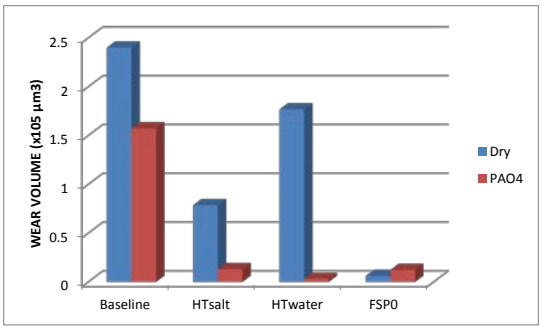

Fig.5: Wear volume measured for the baseline, HT water, HT salt and FSP specimens tested under dry (blue) and lubricated (red) unidirectional sliding contact.

Worn surfaces were examined by optical microscopy and SEM. Figure 6a, show the degree of wear damage for the 4 materials analyzed tested under dry conditions. The baseline material involved the most plastic deformation as indicated by material pile-up at the edge of track, followed by the heat treated specimens and FSP where plastic deformation was minimal. Observation of the wear tracks by SEM showed that the wear damage for the baseline consist mostly of abrasion, as shown by scratches in the direction of sliding and fatigue as illustrated by cracks formation and material loss. For the heat hardened and FSP flats, abrasion, fatigue and material removal occurred in a lesser degree, with FSP exhibiting the least damage.

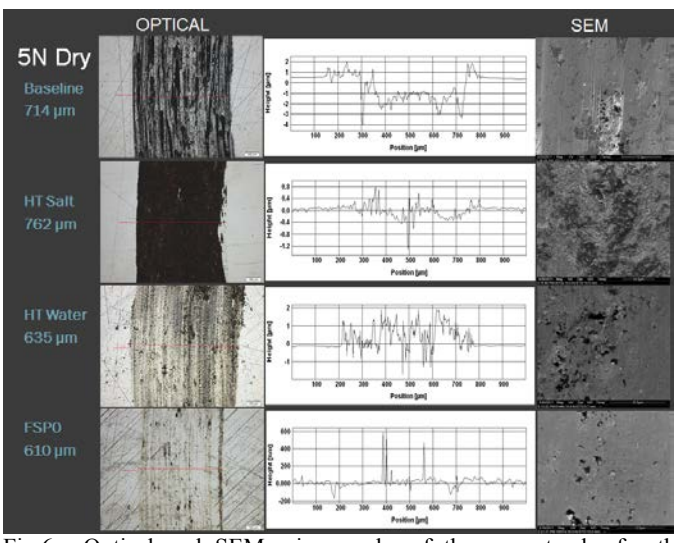

Fig.6a: Optical and SEM micrographs of the wear tracks for the baseline, HT water, HT salt and FSP specimens tested under dry unidirectional sliding contact.

Similar results were observed in the lubricated tests (figure 6b). The baseline material exhibited the most plastic deformation and wear damage (abrasion, fatigue and material removal), while FSP specimen exhibited the least damage. It is worth noting the massive amount of wear debris produced in the salt quenched specimen under dry sliding. More work needs to be done to investigate the mechanisms involved.

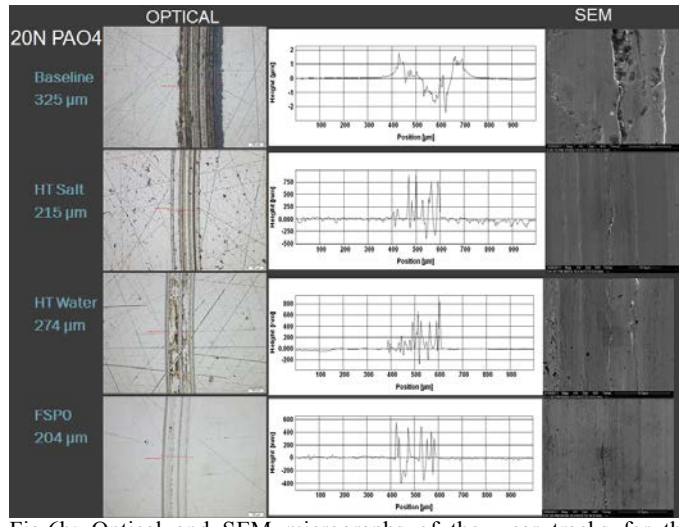

Fig.6b: Optical and SEM micrographs of the wear tracks for the baseline, HT water, HT salt and FSP specimens tested under lubricated unidirectional sliding.

CONCLUSIONS

Results of the present study showed that FSP has an excellent potential to increase hardness and enhance wear resistance of 4140 steel. This improvement in wear behavior can be attributed to microstructural changes in the near surface material consisting of phase transformation and grain refinement. The results showed that the steel can be successfully hardened to a level comparable to the conventional heat treatment and quenching procedure. While the friction behavior of the baseline, heat hardened and FSP materials are similar, significant improvement in the wear performance was observed with FSP.

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