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Short technical note

The effect of laser shock peening on the life and failure mode of a cold pilger die

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ABSTRACT

The laser shock peening (LSP) process was used to increase life of pilger dies made of A2 tool steel by imparting compressive residual stresses to failure prone areas of the dies. The result of X-ray diffraction analysis indicated that deep, high-magnitude compressive residual stresses were generated by the laser shock peening process, and the peened dies exhibited a significant increase of in-service life. Fractography of the failed dies indicates that the failure mechanism was altered by the peening process.

1. Introduction

Cold pilgering is a room temperature, cyclic-forming process in which an input tube is reduced in cross-section by a combination of wall thinning and diameter reduction. Because of the cyclic nature of cold pilgering and the use of water-based flood coolant, the expected failure mode of tools is fatigue, stress corrosion cracking, or corrosion fatigue, the severity of which may be mitigated by the use of surface compressive residual stresses.

Laser shock peening (LSP) is a process that uses a high-intensity laser pulse to generate high residual compressive surface stresses (Clauer et al., 1981). LSP is used in production for titanium and aluminum and is under development for steels. LSP is performed by flowing water over the surface of the component that has been covered with an opaque layer, i.e., a laser-absorbent sacrificial coating, and exposing the water layer and consequently the absorbent-coated layer to a laser pulse. The absorbent coating local to the laser impingement becomes plasma that is constrained by the adjacent coating and water layer, and a pulse of pressure is developed. The pulse of pressure propagates as a shock wave deep into the material and generates compressive residual stresses.

Investigations of LSP-induced residual stresses have been conducted experimentally for various industrial metals. Clauer (1996) compared the effect to LSP on the nature of

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Fig. 1 – A standard pilger die. The location of the residual stress measurement and the orientation of the X-ray are indicated by a circle and a double-headed arrow, respectively in the insert.

residual stresses and the fatigue properties of various metals and alloys based on the results of previously reported studies. Hong and Chengye (1998) and Rubio-González et al. (2004) investigated the effects of LSP on the material properties including fatigue life and fatigue crack growth of 2024-T62 aluminum alloy (Hong and Chengye, 1998) and 6061-T6 aluminum alloy (Rubio-González et al., 2004). The results of the both studies showed that the fatigue life of the LSP processed specimens were significantly improved. According to Hong and Chengye (1998), the fatigue behavior improvements were attributed to a combination of increased dislocation density, decreased surface roughness and compressive residual stress induced by the laser shock waves. Montross et al. (2002) also provided an excellent review regarding the current status of research and development on LSP.

The objective of this study was to investigate the effect of LSP on the life and failure behavior of pilger dies made of A2 tool steel. First, the life of a LSP processed die (or simply LSP-die) was determined by in-process inspection of the formed tubes. Next, the residual stress on the LSP-die as a function of depth was measured by X-ray diffraction (XRD) analysis and chemical milling. Finally, the failure of the LSP-die was analyzed using a scanning electron microscope (SEM). The life, residual stress, and the failure of the LSP-die were compared with those of a die made by a standard die production process.

Table 1 – The chemical composition (wt%) of A2 tool steel

C	0.95–1.05
Cr	4.75–5.50
Si	0.5 max
Ni	0.3 max
Mn	1.00 max
Mo	0.9–1.40
V	0.15–0.50
Fe	Balance

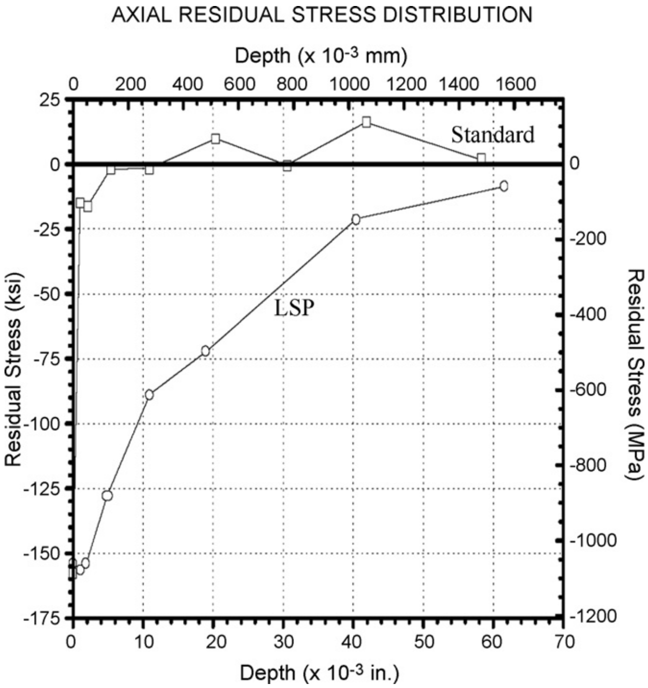

Fig. 2 – The results of the residual stress measurement for the LSP-die and the standard die.

2. Methods

The pilger dies used for this study, as shown in Fig. 1, were fabricated from A2 tool steel with a hardness of between 57 and 59 Rockwell C by double tempering at 510 °C. The chemical composition of A2 tool steel (ASM, 1993) is listed in Table 1. The tapered-groove in the die was ground in a stepwise movement with a circumferential sweeping pattern across the section of the groove. The pilger reduction selected for the test was a pass used to produce a nominal 6.35 mm outside diameter (OD) Ti3Al2.5V texture-controlled aircraft hydraulic tube from an input tube with an initial OD of 9.14 mm with 78% reduction of area. The LSP-dies were prepared by laser shock peening

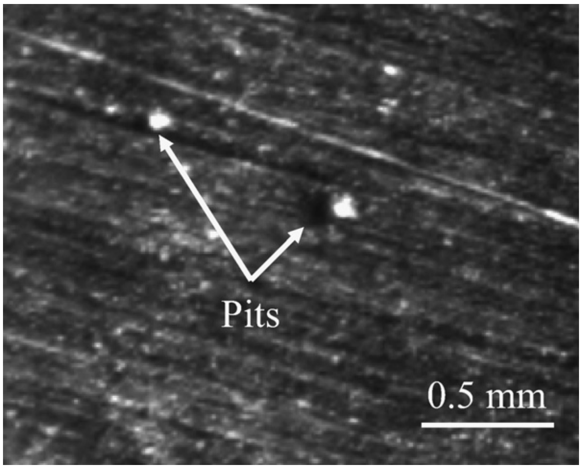

Fig. 3 – Surface appearance of the LSP-die before experiments.

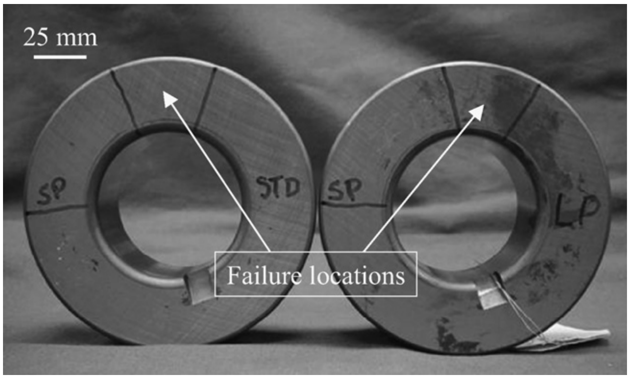

Fig. 4 – The failure locations of the LSP-die and the standard die relative to the key slot.

of standard dies at LSP Technologies Inc. (LSPT; Dublin, OH) using a power density of 10 GW/cm^2. Standard dies that had not received any peening were used as a comparison to the performance of the LSP-dies.

The life of the pilger die was determined by in-process visual inspection of the tubes being processed. Visual inspection of the OD surface of the in-process sample tube, selected on a pre-determined schedule, was performed to look for evidences of die cracks. When the pilger die begins to crack, a small impression of the crack is rolled into the tube surface and is visible to a trained operator at 35× magnification. As the pilger process cycles the die, the crack grows and the impression becomes larger. When the crack impression could not be removed from the tube surface with light sanding using 400 grit sandpaper, the die was considered "cracked-out" and the length of the tube processed for the die was recorded as the life of the die.

XRD residual stress measurements were performed on the LSP-die and the standard die using the $\sin^2\psi$ method in accor-

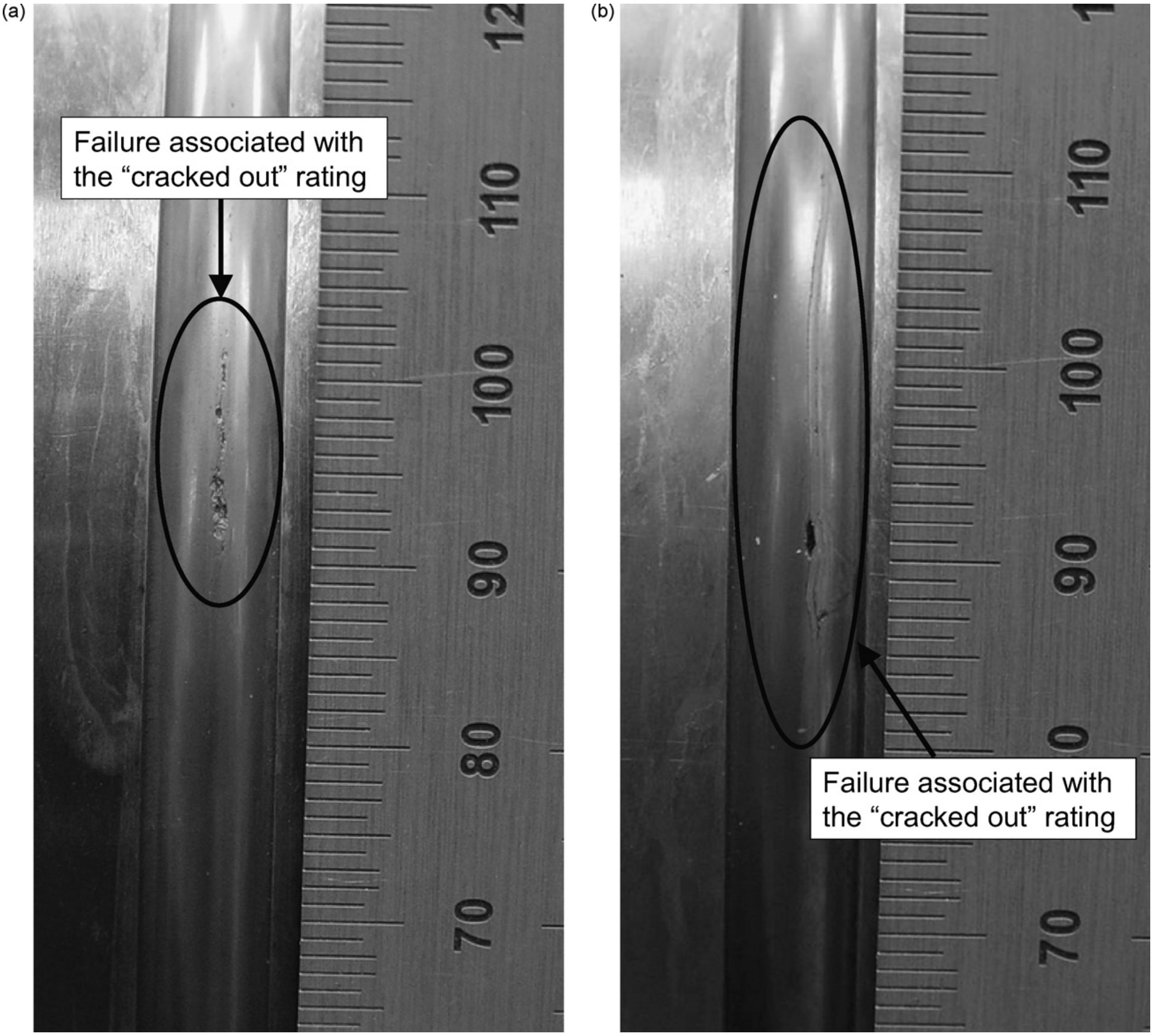

Fig. 5 – The failure regions associated with the "cracked out" rating for (a) the LSP-die and (b) the standard die, respectively. Note that the unit of the scales in the pictures is mm.

dance with SAE HS-784 (2003), employing the diffraction of Cr Kα radiation from the (2 1 1) planes of the BCC structure of the A2 steel. The XRD residual stress measurements were made at the surface and at various nominal depths up to approximately 1.6 mm. The location of the residual stress measurement and the orientation of the X-ray are indicated in the insert in Fig. 1 by a rectangle and a double-headed arrow, respectively and indicating that the X-ray was oriented to best approximate the hoop residual stress.

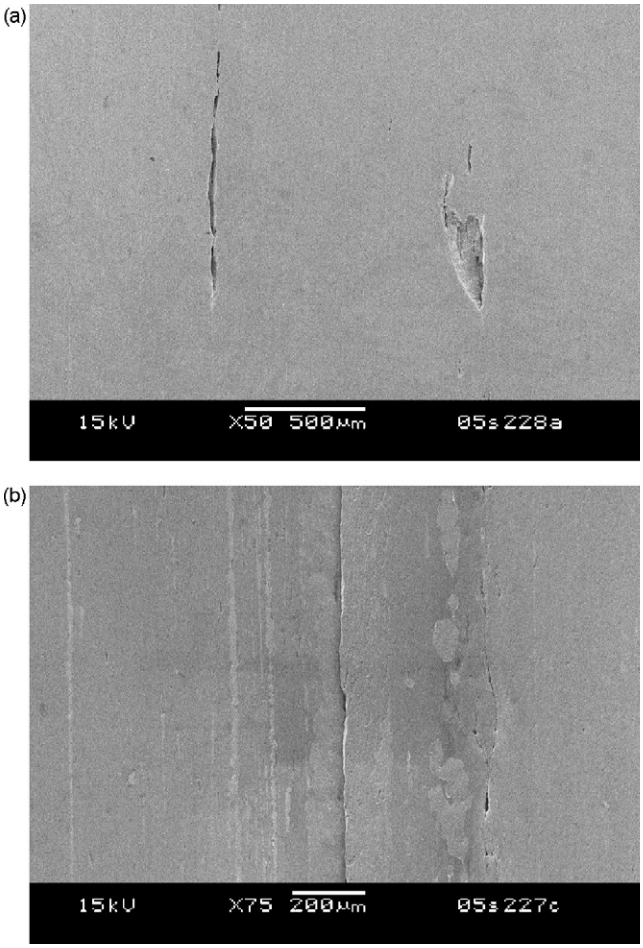

Fig. 6 – Cracked areas approximately 25 mm from the "cracked out" regions shown in Figs. 4 and 5 for (a) the LSP-die and (b) the standard die, respectively.

3. Results and discussion

The LSP process was effective at creating deep compressive residual stress in the root radius of the pilger die. As shown by the residual stress plot in Fig. 2, the LSP-die and the standard die showed similar compressive residual stresses (≈1.05 GPa) at the surface. However, at approximately 0.01 mm depth, the residual stress in the standard die dropped to near 0 whereas the residual stress in the LSP-die was still nearly 900 MPa. Remarkably the LSP-die had a compressive residual stress of approximately 200 MPa at 1 mm depth and the residual stress finally dropped to near 0 at about 1.5 mm depth.

The die surface finish was visually inspected after LSP, and pits were observed. The pits were attributed to the peening process and were subsequently eliminated in later LSP trials; the LSP-dies discussed in this paper had the pitting. The morphology of the pits is shown in Fig. 3 and they were found to be approximately 0.2 mm in diameter and very shallow (creating difficulties for photographing). However, even with the small pits, the LSP-die-set produced approximately 300% more tubing than the average standard production die set before failure and showed the highest die life ever measured for this pass. The increase of 300% represented a statistically significant life improvement and was more than 8 standard deviations greater than the average standard production die life.

The LSP-die failed in nominally the same location relative to the fixed key slot position as the standard die as shown in Fig. 4 and the location is typical of standard production die failure location. Note that the location of the groove within the die is controlled by a key slot used to index the die in the grinder. The optical photographs in Fig. 5(a) and (b) show the specific regions of the die associated with the "cracked out" rating from the previously described visual inspection for the LSP-die and the standard die, respectively and suggest that the failure of the dies was related to the cracks/pits in the root of the groove. The occurrence of the failure in the root of the groove is reasonable since the pilgering process, which reduces the diameter of the tube, induced an opening mode to the groove, and it is intuitive that the highest stress should occur at the root of the groove. Importantly, Fig. 5(a) and (b) also shows that the die cracks in the standard die had propagated along the groove out of the field of view whereas the cracks in the LSP-die were rather isolated and did not propagate much. The difference in the crack propagation behavior of the LSP-die and the standard die also can be seen in the SEM micrographs in Fig. 6(a) and (b), which were taken at approximately 25 mm to the narrower end of the tapered-groove from the "cracked out" regions. Fig. 6(a) and (b) confirms that the LSP-die shows scattered short cracks in the damaged area in contrast to the continuous cracks in the standard die.

Higher magnification views of the regions associated with die "crack out" are given in Fig. 7(a–c). Comparison of Fig. 7(a) and (b) shows that the LSP-die failed by a flaking process rather than a sharp propagating crack as observed in the standard die. With a higher magnification in Fig. 7(c), it can be seen that there are no sharp or propagating cracks associated with the cracked out region of the LSP-die and that materials has flaked and fallen from the die as opposed to the relatively undeformed and failed section of the standard die in Fig. 7(b).

The "flaked" appearance of the LSP-die failure could be related to corrosion given that the extended life resulted in the die being in the mill for many more days, however more likely the flaked appearance of the LSP-die failure may be related to the interaction of the crack process zone and the deep (and high) compressive residual stress similar to that described by Rosenfield (1981) for sheet rolling dies. In this scenario the die fails by plastic deformation and ultimately "flaking" rather than the easy crack propagation observed in low fracture toughness materials like A2. Given the extended life, it is also possible that the failure of the LSP-die has been

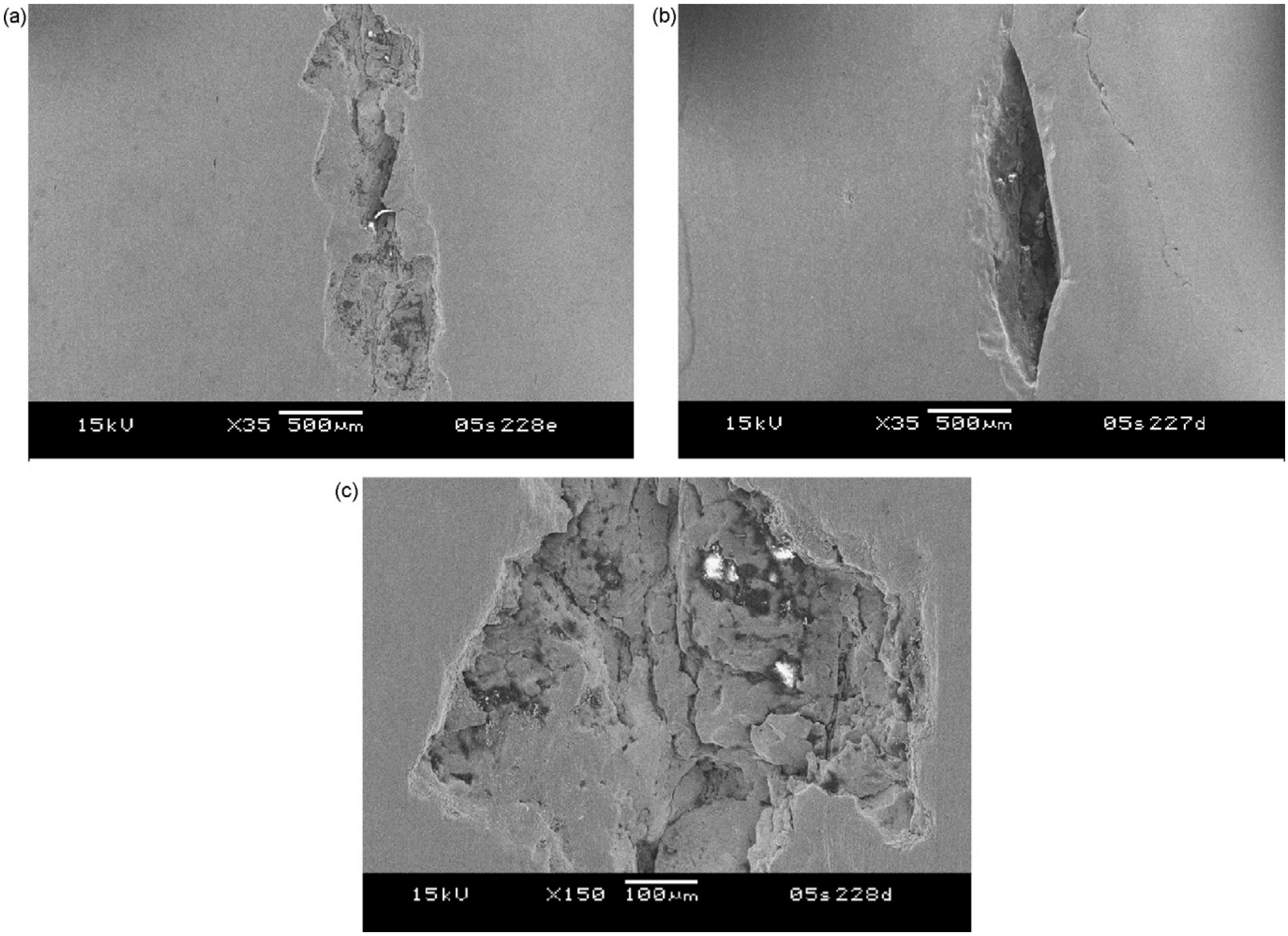

Fig. 7 – SEM images of the most severe regions of the cracks for (a) the LSP-die and (b) the standard die, respectively. (c) A higher magnification of the failed surface of the LSP-die in Fig. 6(a).

originated from other mechanism, for example, wear or friction.

It is possible that the pits associated with LSP process caused the small and isolated cracks, which may accelerated the initiation of the "flaked" appearance failure of the LSP-die. Undoubtedly, the cracks would ultimately propagate and some of the LSP-die cracks are sharp, as shown in the left side of Fig. 6(a), however due to the very high compressive residual stress the crack growth rate was slowed and consequently the LSP-die failed ("cracked out") by a different mechanism prior to the crack propagation like that observed in the standard die.

4. Conclusions

As a result of this study the following conclusions were reached:

- LSP was effective at generating deep compressive residual stresses in the pilger die groove. At a depth of 0.1 mm the compressive residual stress in the LSP-die was 900 MPa and while the compressive residual stress in the standard die was nearly 0 at the same depth.
- LSP was effective at increasing the life of the pilger die as measured by the length of tubing produced. The laser processed die had the highest life of all dies used to process this tube size and exceeded the average die life by three times.
- Pitting associated with laser peening process appeared to contribute to the observed cracking in the die and may have limited the die life.
- The failure appearance of the laser-peened die is different from the standard die and may have been related to corrosion or high compressive forming stresses that prevented crack propagation. The die failure mode was changed from the classic crack propagation observed in low toughness steels to plastic deformation that resulted in flaking.

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