CHARACTERIZATION OF MATERIALS DEPENDENT PROPERTIES IN SHOT PEENING AND FATIGUE

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ABSTRACT

Shot peening technology is a kind of cold working processing that changes the macro-morphology and micro-structure as well as residual stress state in the surface layer. Great attentions have been paid to shot peening induced residual stress and its relaxation behaviour during fatigue, but only a few researches were focussed on changes in microstructure and its effect on residual stress and fatigue. In the present paper microstructure-dependent properties of shot peened materials are demonstrated. It is stated that an initiation of fatigue crack can be delayed even without compressive residual stresses in the shot peened surface layer, compressive residual stresses in the surface can possibly be increased other than reduced if there is a phase transformation during fatigue, and shot peening induced residual stresses will be concentrated at a notch and result in a big improvement of fatigue strength when the treated material has a strong resistance to yielding and to elastic recovery. It is therefore necessary to take materials dependent properties into account in dealing with shot peening related problems.

Key Words: Shot peening, residual stress, microstructure, fatigue.

INTRODUCTION

Shot peening is one of the most popular tools for mechanical surface treatments that are frequently used in, for instance, automobile and aeronautic industries. Some components are not allowed to despatch from a factory without being shot peened, and some work pieces in use have to be re-peened for repairing
and healing of the damages caused during service. Different shot peening technologies have been developed in the past decades such as double peening, thermal peening and pre-stressed peening, and all of which aim at introducing a well distribution of compressive residual stresses in the surface layer[1]. In a matter of fact, the compressive residual stress is considered the most essential parameter by most majority researchers in controlling corrosion resistance and fatigue strength of shot peened components. Nevertheless, to the engineer the residual stress and applied stress are completely separate entities, although both are manifested in identical physical mechanisms on an atomic scale. The residual stress introduced by shot peening is a material-dependent as well as mechanical-dependent parameter. It shows quite different patterns in different kind of material or materials state with the same mechanical peening process. It will also change under thermal-mechanical condition with changes of microstructure in components. This characteristics of shot peening induced residual stress is not yet fully recognized in industries, and some engineers are not well concerned with the microstructure and the property of materials used.

It becomes more and more necessarily to have a quantitative design of the modern material and structure on the account of energy-efficiency, materials-saving, as well as long term reliability and functionality. This may be one of the reasons that there are many advanced models proposed based upon theoretical estimation of shot peened induced residual stresses and their mechanical influences on fatigue crack growth of a definite material [2-3]. It was expected that the fracture of the component involved with particular surface treatment such as shot peening could be predicted as it is at an apparently applied load. But it is eventually realized that though the processing appears simple the shot peening is really a complicated phenomenon and not only concerned with the original residual stress itself. The mechanical properties of surface layer will be altered by shot peening in such a way that both static and cyclic strength are increased or decreased depending upon the material state before
shot peening. This is due to cyclic plastic deformation of surface layer during shot peening, which implies that the fatigue life or stress corrosion resistance would be altered by microstructure except for residual stress.

It is also realized that the compressive residual stress induced by shot peening would be possibly released more or less during fatigue, and its effect on fatigue strength cannot be evaluated with its original value. There are many investigations on relaxation behaviour of residual stresses under different loading conditions [4-5], but the point is that the relaxation is strongly related to material tested. It is only when there is a crack extending through the residual stress field that the relaxation of residual stresses becomes less and less related to material and its properties. We found that in some circumstances there is an abnormal increase of residual stress during fatigue, indicating strengthening other than weakening of materials in the cyclic loaded region.

The influence of material itself on shot peening induced residual stress and its relaxation behaviour during fatigue can hardly be underestimated specially for a notched part. Theoretical calculation of residual stresses induced by shot peening or cold expansion around a notch or a hole is particularly required since it is very difficult to obtain the data of residual stresses experimentally. It has long been acknowledged that the effect of mechanical surface treatments on fatigue of material with notches or holes is much more pronounced [6]. We once stated that the reason might lie in the fact that there is a residual compressive stress concentration at the notch when it is treated by shot peening, and usually a non-propagating crack appears during fatigue at the notch root that reveals the transition of controlling factor of fatigue limit from crack initiation to crack arrest in a compressive residual stress field [7-8]. There is a fundamental difference between the conventional stress concentration and the so-called residual stress concentration. The conventional stress concentration is only a function of applied load and geometry of the notch, while the
residual stress concentration depends to a great extent on materials strength in addition to the notched size and the mechanical treating process. This material-dependent property of shot peening induced residual stresses has not yet been explored clearly, and sometimes even appears extremely problematic.

The emphasis in the present paper is focussed on shot peening induced materials-related changes in microstructure and residual stress. Some examples will be given based on previous studies that aimed at exploring materials functions during shot peening and fatiguing of the material. It becomes well recognized that the technique of shot peening is a materials processing as well as mechanical surface treating. The response of the material treated and its resultant action on fatigue or corrosion should be paid a great attention.

SHOT PEENING AFFECTED LAYER IN THE SURFACE

A special technique has to be used to study on effect of microstructure since both state of residual stress and microstructure in the surface layer are altered by shot peening and their influence on fatigue crack initiation and growth is usually mixed up. We found that the shot peening induced residual stresses in the surface layer can be removed and the deformed layer will be left if the following procedure is applied [9]. It is shown schematically in Fig. 1. In a first step shot peening is made on both sides of a flat specimen to introduce residual stresses and deformed layer in the surface and the surface layer of one side (termed as side A) is removed mechanically. Since there are no more residual stresses acting on the left part in side A, the residual stresses in the other side (termed as side B) are released correspondingly down to small values for a requirement of internal stress balance in the whole section of the specimen. Finally the processing of shot peening is again applied but only on the surface of side A.
With this treatment the specimens will have a residual stressed and plastic deformed layer in side A and a free-stressed layer involved only with shot peening induced plastic deformation in side B. Fig. 2 demonstrates a through-depth-distribution of shot peening induced residual stresses in copper and brass, and Table 1 shows the value of residual stress measured on the surface of side B. It is evident that much higher compressive residual stresses can be introduced into the surface layer by shot peening, but the stress on side B will be released to a great extent when the surface layer in the opposite side is removed. The re-introduction of residual stresses by second shot peening on side A has no detectable influence on stress state in side B. The residual stress inside B can be neglected as compared with that in side A.
We did not notice the different response between side B and side A in fatigue, although we realize in the later experience that with this test an ability can possibly be distinguished of compressive residual stress to resistant to crack initiation. In the test the fatigue life of specimens with and without shot peening and the morphologies after fatigue testing were compared. An example is given in Fig. 3 in which the visible persistent slip band (PSB) on the surface of the non-shot peened copper and fatigue cracks on the bottom of the PSBs under a higher magnification can hardly be examined on the surface of side B which was not shot peened and residual stress released. Table 2 is the tested result of copper and brass, indicating that even without compressive residual stress the plastic deformed layer itself induced by shot peening is capable of preventing premature initiation of fatigue crack. Such a kind of ability appears to be strong for work-hardening materials like brass.

Table 1. The residual stress on the surface with different peening and/or thinning processes.

<table>
<thead>
<tr>
<th>Material</th>
<th>Group A</th>
<th>Group B - side B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>side B after removal of side A</td>
<td>side B after peening on side A</td>
</tr>
<tr>
<td>Cu</td>
<td>-120MPa</td>
<td>-26MPa</td>
</tr>
<tr>
<td>Brass</td>
<td>-510MPa</td>
<td>-47MPa</td>
</tr>
</tbody>
</table>

Table 2. Comparison of fatigue life between specimens A and B.

<table>
<thead>
<tr>
<th>Material</th>
<th>Loading amplitude</th>
<th>Without SP</th>
<th>SP- side B</th>
<th>Increment, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>280MPa</td>
<td>5.9x10^4</td>
<td>1.7x10^5</td>
<td>288</td>
</tr>
<tr>
<td>Brass</td>
<td>315 MPa</td>
<td>7.5x10^5</td>
<td>&gt;5x10^6</td>
<td>&gt;400</td>
</tr>
</tbody>
</table>
This result reveals that in addition to compressive residual stresses the shot peening induced plastic deformed layer must be taken into consideration in analysis and estimation of fatigue strength of material and structure. The solution would be simplified if the deformed layer is mainly dominant to crack initiation and the residual stress is strongly related to crack propagation.

**ANTI-RELAXATION OF RESIDUAL STRESS RELATED TO PHASE TRANSFORMATION.**

The relaxation behaviour of residual stresses is an essential problem for performance and life prediction of shot peened material and structure. It is common to nearly all of materials that the shot peening induced compressive residual stress must be released during cyclic loading when the superimposed stress of residual and applied ones is beyond the static and cyclic yield strength. It is usually admitted that the benefit of shot peening is more pronounced for components serviced under a high cyclic region. There are few tests carried out in a low cyclic region especially for a stainless steel.
Recently such a test was performed in our laboratory and surprisingly it was found that the shot peening induced compressive residual stress was increased other than decreased during fatigue. The plot in Fig. 4 is one of the results measured on ASTM A201 after fatigue testing. It is an austenite stainless steel but during shot peening a second phase of martensite with about 30% in volume was formed in the surface layer. The measurement result reveals that both phases of austenite and martensite are involved with compressive residual stress in the shot peened surface, and after a number of cycles in fatigue the absolute values of residual stresses get up with cyclic numbers. The phenomenon differs quite a lot to the normal case of shot peened samples. Fig.5 is a normal pattern of the stress relaxation in the nickel-based alloy, Inconel 600, that is a single-phase material and shot peened and fatigue tested under an identical condition.

Fig.4. Residual stress vs. cycle in Inconel 600
It should be pointed out at the loading stress in both tests was high enough and nearly reached to the yield strength of each material. This kind of low cyclic fatigue test is usually not applied to shot peened components because of rapid relaxation of compressive residual stresses. Nevertheless, the tested austenite stainless steel is of characterization of strain-induced phase transformation. When the applied stress in fatigue is increased in such a level that causes the austenite transformation in stress concentrated area in the matrix, the whole pattern of residual stresses would be changed. There are some researches on shot peened dual-phase materials such as brass and titanium alloy with $\alpha$ and $\beta$ phase, but few papers in the literature have been concerned with phase transformation during shot peening and fatigue loading. This anti-relaxation behaviour of residual stresses may imply complex changes in internal stress pattern, but at present the detailed mechanism is unable to explore. It is postulated that if there is phase transformation during fatigue the residual stresses especially the austenite phase will be increased because the martensite is a hard phase with higher yield strength and also results in volume expansion during transformation. Some weakened area with micro-holes and micro-cracks possibly induced by over-peening in the matrix will also be renovated by such kind of phase transformation.

Fig. 5. Residual stress vs. cycle in ASTM A201
CONCEPT OF RESIDUAL STRESS CONCENTRATION AT A NOTCH

Mechanical surface treatment such as shot peening and cold expansion are most powerful for a notched part under cyclic loads since an initiation and premature growth of fatigue crack can be restrained to some extent. But it is hard to measure the residual stresses at the root of a notch, and hence hard to predict an increment of fatigue strength or fatigue life before test. Care must be taken if the measurement result on smooth part or notch with larger radius is going to be used for notches with smaller radii. Fig. 6 shows the results measured on a round bar and a plate made of hard steel. The same peening parameters or the same rolling forces was applied on the smooth and notched part, but the distribution pattern of the residual stresses induced is quite different. The compressive residual stresses are larger and distributed deeper at the notches, implying residual stress concentration in a limited area in general with the same surface treatment, a sharp notch will have a high magnitude of residual stress than a blank notch.

![Fig. 6. Residual stress distributed in distance on smooth part and notched part [10]](image)

However, the residual stress concentration is not exactly the same as conventional stress concentration that is solely determined by geometry of notch. The residual stress concentration in materials
dependent and usually needs to take into consideration for materials with high yield strength and high work-hardening exponent. There appeared no much difference of shot peening induced residual stresses of mild steel, indicating that the measured values on a smooth part can be used for a notch. But it must be borne in mind that the mechanical surface treatment is seldom used on soft materials due to relaxation of residual stresses in fatigue and a limited effect on the mechanical properties of structures.

Fig. 7 shows the distribution of residual stresses both along the depth and the thickness of a flat specimen at notch root. The notch was surface rolled in a similar way as cold expansion, and the measured spot of 0.2mm X-ray beam in diameter was right on the notch root. It was evident that for the low temperature tempered steel the residual stresses vary greatly not only along the depth but along the thickness as well. This measurement was in a quite agreement with the fatigue test in which the convex front of crack could be detected on the fractured surface. It also implies that measurement on the lateral side of notch might not give full information of residual stresses for materials with high strength.

![Graph showing residual stresses distribution](image)

Fig. 7. The distribution of residual stresses both along the depth and the thickness of a flat specimen at notch root.
The reason that residual stress tends to concentrate at a notch of high strength material lies in the fact that the residual stress in most cases of plastic deformation in a local region and strong constraint of elastic body around it. Heavily plastic deformation usually leads to high magnitude of residual stresses, but there will be no much accumulation of residual stresses if a full recovery of the plastic deformed body can be completed freely. Fig.8

![Fig.8 Exhibits the variation of a full width at half maximum (FWHM)]()

Exhibits the variation of a full width at half maximum (FWHM) of X-ray diffraction profile measure on the same sample as in Fig.7. It is clear that plastic deformation induced by surface rolling at notch root is more serious in the interior beneath the root surface of notch but keeps nearly constant along the thickness. It follows that the different concentration of residual stresses along the thickness of notch is mainly controlled by elastic constraint after surface rolling on the root of notch. The plane stress state near the lateral side of notch may allow much recovery of the deformed materials and hence results in relatively small values of accumulated residual stresses.

**CONCLUDING REMARKS**

Theoretical modeling and numerical simulating of mechanical surface treatment and its effect on fatigue at different service conditions have long been a concern of scientist and engineer. More and more researches have realized an important role of
materials dependent properties in estimation of fatigue failure of shot peened components. But it still remains unsolved to have a universal tool measuring and evaluating changes of mechanical properties in the deformed surface layer. A nano-crystallized microstructure was claimed to be able to produce by ultrasonic shot peening in the surface layer [12]. Its mechanical properties in this case must be different to corresponding bulk material.

An advanced nano-indentation test will become a potential method to evaluate changes of mechanical properties in the deformed surface layer. It was proposed originally for determination of micro-hardness and elastic modulus of thin solid films [11], and later extended to evaluation of creeping and yielding behaviours but still for coated films [13-14]. There are a few researches using this novel technology on the surface layer deformed by cold working. It is expected that changes of mechanical properties as well as residual stresses in the surface layer can be measured precisely and eventually be predicted with a reasonable model.

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