TEMPLATE
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Picture related to the research project

A new method for waterjet peening process improvement using a combination of waterjet surface hardening and polishing

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ABSTRACT

The present study investigates a combined effect of waterjet peening and smoothing on the surface of austenitic stainless steel 304. An analysis of surface and sub-surface integrity was conducted. The waterjet treatment on the surface was done in steps with multiple passes. The surfaces treated with multiple steps of decreasing energy produced a smoother surface with lower peak heights and a slightly higher increase in the hardness than the surface treated with only a single step. The results of XRD measurements showed that a higher amount of compressive residual stresses is induced in the treated specimens. This strengthening layer is limited within the first 100 µm below the surface, which had been confirmed by micro hardness measurements. The combined action of surface hardening and smoothing using multiple steps in waterjet treatment is useful in increasing the hardness and reducing the roughness of the surface. However, the treated specimens showed that the fatigue limit is lower than that of the untreated specimens. The slight roughness of the surface and the resulting notch effect seems to be stronger than the positive effect of the strengthend layer.

1. INTRODUCTION

In today's practice, mechanical surface treatments have been widely applied particularly in the spring-manufacturing, automotive and aerospace industries. Furthermore, these processes are known to be well established already in ancient times concerning metallic materials where evidently hammering was the first mechanical method used to make particular components to final shape and strength [1]. It was realized that the failure due to fatigue depends on many factors, and very often it develops from particular surface areas of engineering parts. So, it seems possible to improve the fatigue strength of metallic components by the application of suitable mechanical surface strengthening processes [1]. These processes such as shot peening (SP), laser shock peening (LSP) and waterjet peening (WJP) are known to induce beneficial compressive residual stresses into metallic surfaces which may improve the resistance against fatigue crack initiation and propagation [2].

The material surface plays an important role in the response of the engineering components. They are often subjected to various surface treatment processes to achieve certain qualities that are not available from the primary manufacturing processes. The process is conducted for various reasons including the improvement of the material performance, the changing of physical properties and the variation of the appearance and dimensions. A diverse range of thermal, mechanical and chemical treatments has been developed to modify the surface characteristics. Various surface treatment processes have been used for a wide range of materials from semiconductors to metals, ceramics, polymers, and bio and nanomaterials. The mechanism of fatigue improvement is rather complex and it is difficult to draw a direct comparison of the effects due to the interaction of positive effect (i.e. high compressive residual stress) and negative effect (i.e. high roughness) after such treatments.

2. RESEARCH METHODOLOGY

A technique to smooth the surface in the multiple waterjet passes treatment is by performing a polishing action on the surface with the subsequent jet passes. Firstly, the material surface is treated with sufficient kinetic energy during initial jet passes so that an optimum compressive residual stress and hardness can be induced with suitable erosion. Finally, much lower kinetic energy of the jet is used during subsequent passes hence only unstable fragments of material introduced from previous surface erosion can be removed. As a result, it is believed that the surface can be smoothed while maintaining the initially hardened layer. Consequently, the smoother surface of the treated specimen may produce higher fatigue strength since fatigue crack initiation is discouraged with the formation of smoother surface. The waterjet surface treatment was carried out using the waterjet machine. The specimen was treated along the width of the specimen with pre-determined parameters as shown in Fig. 1.

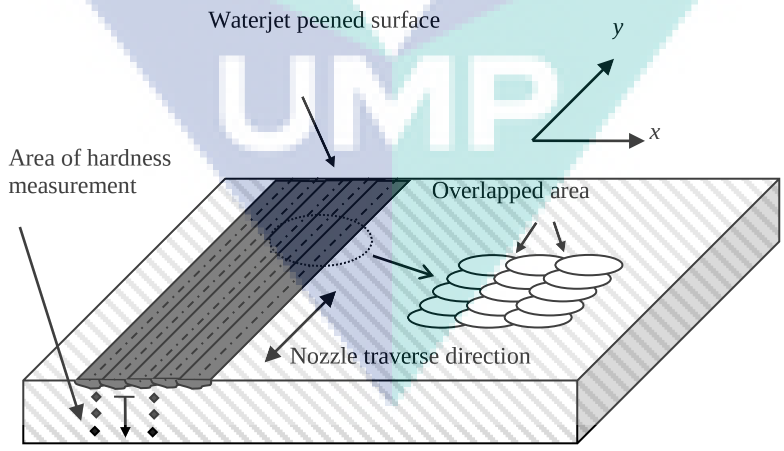


Fig. 1: Schematic of WJP treatment

3. LITERATURE REVIEW

Many investigations show an increase in the surface roughness after SP [3, 4], LSP [5, 6] and WJP [7-10] however, the results also show a higher fatigue lifetime due to the introduction of a higher compressive residual stress as well as a higher penetration depth of work hardening. Furthermore, it is a fact that rougher surfaces are expected to encourage fatigue crack initiation [11]. The benefit of compressive residual stresses may be defeated by the negative effect of surface defects which may just act as the crack initiation sites during the fatigue test. These observations are reported in shot peening [4, 12] as well as laser shock peening [5, 13]. Therefore, it would be interesting if the surface erosion can be minimized while achieving the optimum effect of work hardening during the waterjet peening treatment. The technology and applications of high pressure waterjet have been studied since many decades (as early as 1960s) [14]. It has been used extensively in various industry-related applications including machining, surface preparation, cleaning, coating removal and surface treatment like waterjet peening (WJP). WJP is a relatively new application of the waterjet technology [15]. It is a mechanical surface strengthening process where high-frequent impact of water drops on the surface of metallic components, which causes local plastic deformation.

As a result, high compressive residual stresses are induced in the surface near layer of the workpiece, which leads to enhanced surface hardness and fatigue life [16]. With an addition of abrasive particles, a higher amount of compressive residual stresses is induced but with a significant increase in roughness of metal surfaces [8]. Furthermore, some of the abrasive particles remain embedded in the surface upon jet impact which may cause a change in surface roughness [17]. Surface roughening of metals can be achieved through high pressure pure waterjet process [11]. Various processing parameters influence the roughness of metallic surfaces. An increase in water pressure results in more erosion loss and a higher roughness of the surface owing to a greater velocity of the jet [7]. A reverse effect can be seen for the traverse speed [11]. Furthermore, rougher surfaces are expected due to repeated bombardment of waterjet onto the surface during multiple jet pass treatment [8, 18]. This implies the roughening of the surface by the subsequent passes. With increased number of jet passes, more material can be removed to form a complete network of eroded surface [8]. Additionally, increasing the energy and frequency of water drops may lead to a higher increase in hardness as well as a deeper hardening layer. This is shown by treating the surface with a higher number of passes which produces a higher increase of hardness as well as a deeper hardening layer [7, 8]. The increase in hardness and thickness of hardening layer is possibly the result of higher amount of plastic deformation from repeated waterjet impacts. However, it is worth to note that increasing the frequency of water droplets to the same areas on the surface (i.e. decreasing the traverse speed) does not always lead to an increase in hardness [19].

4. FINDINGS

In general, the process of water droplet impacts is highly stochastic in nature as shown in Fig. 2. The impacting droplets have not fully covered the surface by leaving some areas of the original surface. However, with more jet passes although at lower energy, repeated impacts have occurred thus covering the whole surface with indents. This indicates that the surface has been repeatedly impacted by the droplets during subsequent jet passes thus leaving no more flat surface for generating new indents [8]. The impacting process in the waterjet treatment is somehow similar to the mechanical attrition treatment using small solid balls [20]. The indents on the surface created by initial impacting droplets are random. Some locations may have covered with repeated impacts although not all areas of the surface are covered by indents. Later with more waterjet treatments, the entire surface may have been covered by indents with some areas have been impacted several times. Additionally, the peak heights are continuously lowered, but the valley depths are not significantly affected by repeated impacts [20].

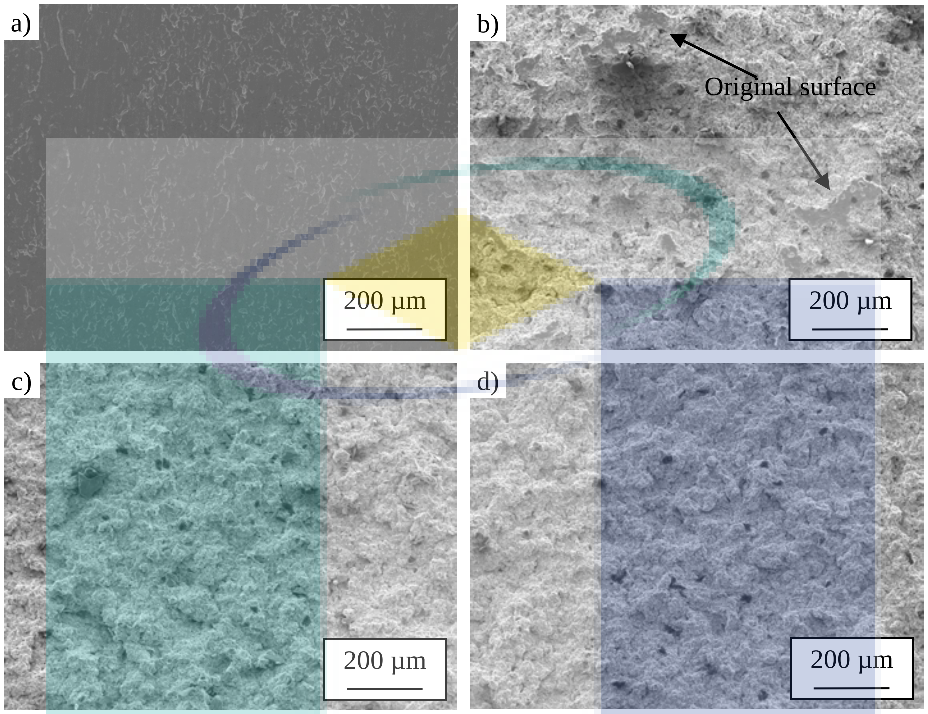
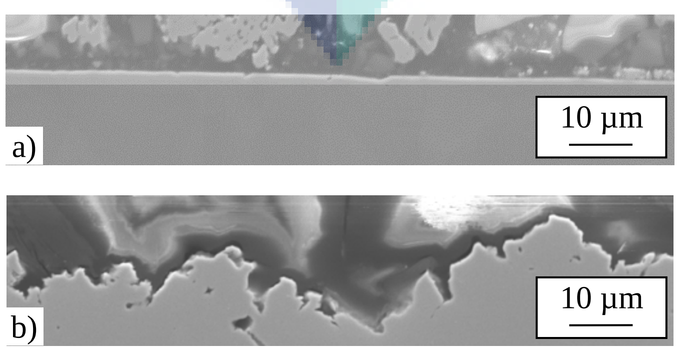


Fig. 2: Surface morphologies of treated specimens, a) original, b) 2 passes, c) 4 passes, and d) 6 passes

The treated specimens at each condition were later sectioned to display their cross-sectional surfaces. Fig. 3 shows the cross-sectional view of the surfaces. In general, all surfaces exhibit relatively similar profiles as discussed above. Due to the stochastic nature of the water droplets impact, all areas in the treated specimens do not experience same level of impacts thus producing an uneven surface. As a result, certain areas have deep valleys and some others high peaks. It is obvious that the treated surface with only first treatment shows deeper notches. While the treated surfaces with second and third treatment show a smoother area with a considerably lower height of the peak-to-valley. This is clear evidence that with second and third treatment of a lower energy level, the height of the peaks has been reduced thus improving the smoothness of the surface.



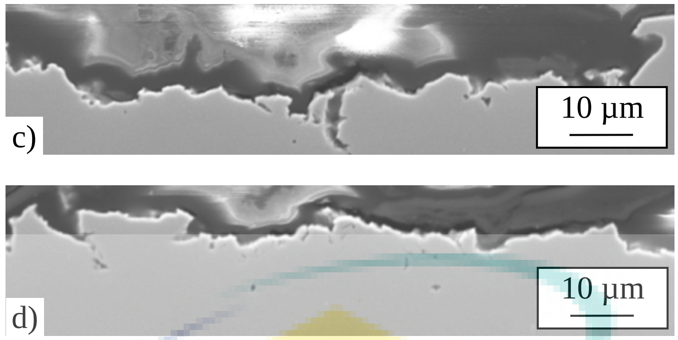


Fig. 3: Cross-sectional views of the treated surfaces at a high magnification, a) original, b) 2 passes, c) 4 passes, and d) 6 passes

Subsurface hardness was measured on the cross-sections of the specimens at different depths starting from 20 μm beneath the jet impinged surface until a far distance of approximately 1,000 μm. The hardness profile for each condition is shown in Fig. 4. In general, the hardness profiles for all conditions show a similar trend with the hardness decreasing gradually from the surface. There are significant changes in hardness values up to a depth of about 100 μm. The average maximum hardness was recorded to be 266, 268 and 293 $HV_{0.005}$ for 2 passes, 4 passes and 6 passes respectively. These constitute to an increase in hardness of about 24%, 25%, and 37% respectively, with respect to the base material which has average hardness of approximately 214 $HV_{0.005}$. In term of the hardening layer, it is difficult to assess due to the scattered hardness data. However, based on outlying lines of power graphs, the hardening layer may extend slightly deeper, especially in the case of 6 passes with triple treatments.

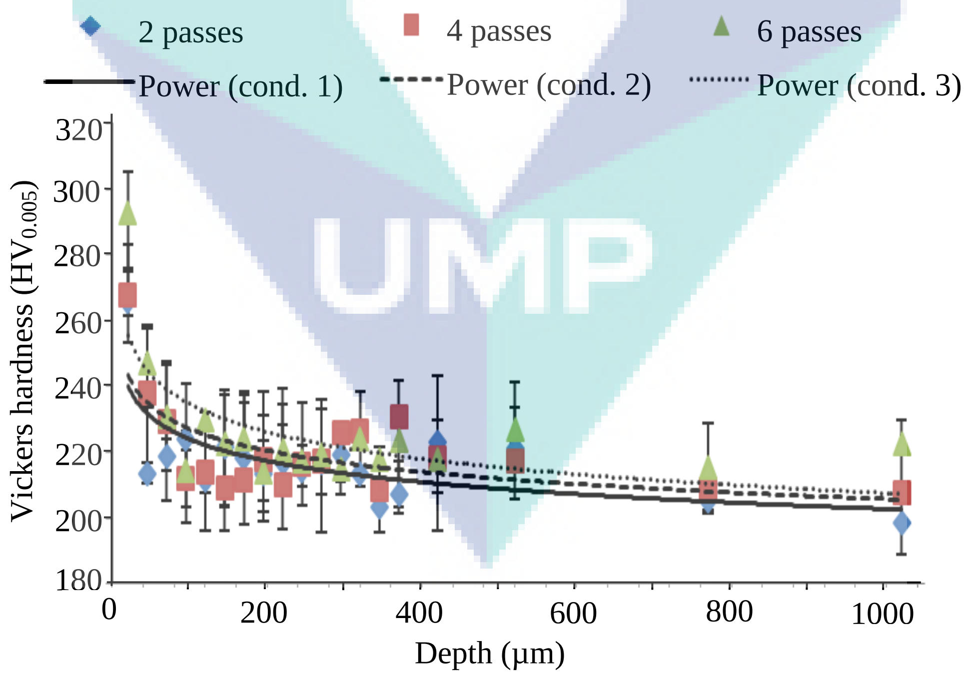


Fig. 4: Effect of different conditions on hardness gradient

Furthermore, the treated specimens were tested for the amount of induced compressive residual stresses. The introduction of compressive residual stresses in the treated specimens was observed to be between 56 to 470 MPa. However, the strengthening layer is limited within 100 μm below the surface. Fig. 5 shows the residual stress depth profiles for the treated specimens in both traverse and longitudinal directions. The specimen treated with the most number of jet passes produced the highest surface compressive residual stress.

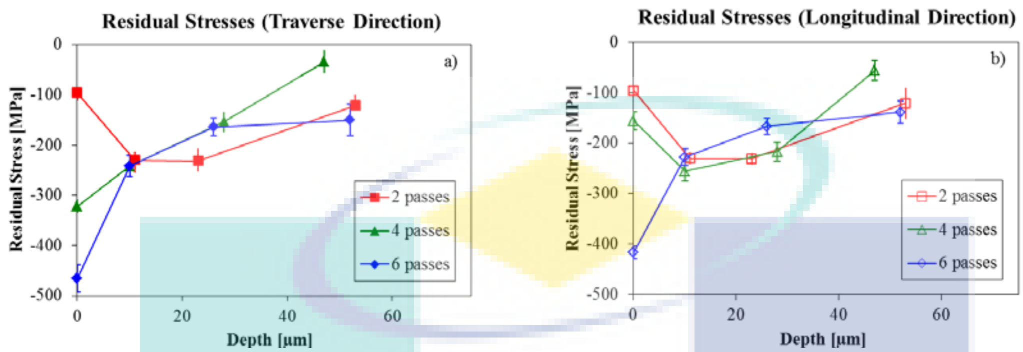


Fig. 5: Residual stress depth profiles for treated specimens in, a) traverse direction and b) longitudinal direction

The results of the fatigue tests are plotted as the stress amplitudes versus number of cycles to failure as shown in Fig. 6. For number of cycles, a log scale is used. Overall, the waterjet treated specimens show a lower fatigue strength than the original specimens. Specimens with the highest increase in the hardness and residual stresses resulted in the largest decrease in the fatigue strength. The specimens treated with the lowest number of passes did not show a decrease in fatigue strength as compared to the original ones. It possibly demonstrates a very marginal increase in the fatigue strength. The results seem to suggest that the influence of the surface roughness is more prominent than the increase in hardness and residual stress in determining the fatigue strength.

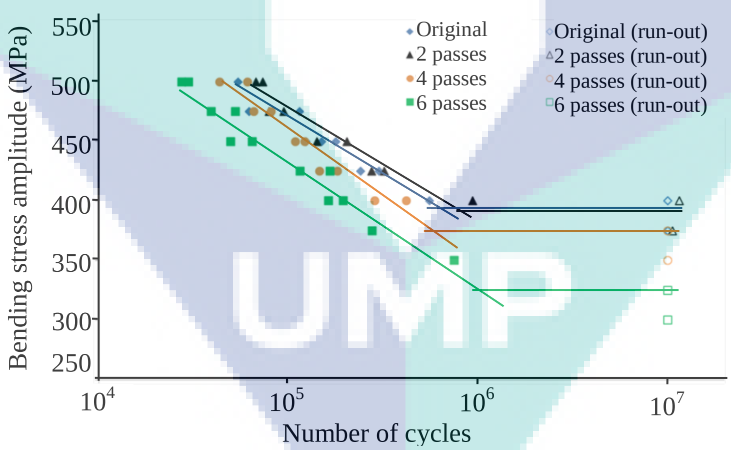


Fig. 6: Stress versus number of cycles diagram for treated specimens

5. CONCLUSION

The effect of combined action of waterjet peening and smoothing on the surface of austenitic stainless steel 304 was investigated. The surface morphology of treated specimens with decreasing energy of water droplets has shown relatively lower amount of peak areas thus indicating a smoother surface. Also, the peak areas and the average of the peak heights were continuously reduced with multiple steps of waterjet treatment. The initially hardened layer from the earlier treatment has shown an increase in the hardness gradient as well as a deeper hardening layer during the later treatment. While the endurance fatigue limit for 2 passed treated specimens is relatively equal to that of the untreated specimens, it decreased with increasing passes. On the one hand side the compressive residual stresses increase with a higher number of passes and also the resulting surface hardness. On the other hand the roughness of the surface increase, so that there are a lot of potential crack initiation sites which leads to the decrease of fatigue strength.

ACHIEVEMENT

i) Name of articles/ manuscripts/ books published

1. Azhari et al., Influence of waterjet peening and smoothing on the material surface and properties of stainless steel 304, Surface and Coatings Technology, 258 (2014) 1176-1182.
2. Azhari et al., Effect of multiple passes treatment in waterjet peening on fatigue performance, Applied Surface Science, 388, Part A (2016) 468-474.

ii) Title of Paper presentations (international/ local)

1. Azhari et al., A review on the application of peening processes for surface treatment. IOP Conference Series: Materials Science and Engineering. Vol. 114. No. 1. IOP Publishing, 2016.
2. Azhari et al., CFD Based Erosion Modelling of Abrasive Waterjet Nozzle using Discrete Phase Method. IOP Conference Series: Materials Science and Engineering. Vol. 114. No. 1. IOP Publishing, 2016.
3. Azhari et al., A review on nozzle wear in abrasive water jet machining application. IOP Conference Series: Materials Science and Engineering. Vol. 114. No. 1. IOP Publishing, 2016.

iii) Human Capital Development

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iv) Awards/ Others

v) Others

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APPENDIXES