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Deep Cold Rolling of Features on Aero-Engine Components

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Abstract

Fatigue limited performance in aero-engine components is one of the critical challenges in the industry. In order to increase the resistance of such components to initiation and early growth of fatigue cracks, especially in the presence of foreign object damage, mechanical surface treatments are widely used. Although shot peening is traditionally being adopted for most aero engine components, deep cold rolling (DCR) offers several advantages over the shot peening process. Although DCR is able to generate a deeper layer of compressive residual stress and good surface finish, one of the challenges in adopting this processs for wider application in the industry is the limitation in applying it to different geometrical profiles. In this study, three cold rolling tool designs were selected to study its feasibility on processing Titanium (Ti 6Al-4V) test coupons of different features. The effect of process variables (pressure, feed rate and overlap) on residual stress profiles were also investigated for one selected tool. Results showed that DCR is able to generate deep layer of compressive residual stress (up to 1mm depth) and process variables such as rolling pressure played a significant role in affecting the residual stress profiles.

Keywords: Deep cold rolling;residual stress, foreign object damage, fatigue, surface enhancement

1. Introduction

The control of failure due to fatigue in aero-engine components is one of the critical challenges in the industry. Components that are generally affected by fatigue are blades and disk which are constantly subjected to HCF loading associated with high frequency vibrations within the engine on top of a low cycle fatigues component associated with start and stop cycles (1). In order to mitigate the risk to fatigue failure and to prevent crack initiation and propagation under the high cycle and low cycle fatigue loadings, especially in the presence of foreign-object damage (2), mechanical surface treatments such as shot peening, laser shock peening or deep cold rolling processes can be employed. These processes are commonly adopted to improved resistance to wear and stress corrosion and in most cases, to improve the fatigue strength of highly stress metallic component in an aero-engine (1).

In most cases, when enhanced fatigue strength is required, shot peening is usually considered and adopted in the first instance as there are considerable process knowledge and equipment know-how within the aerospace industry. However, with new designs being incorporated into components to improve performance in terms of fuel efficiency, this has led to higher requirements in terms of fatigue strength. This is taxing the current shot peening process beyond its capability and deep cold rolling appears to be a viable option as it offers several advantages such as its capability of generating a 'deeper case' of compressive residual stresses, a work hardened structure as well as significantly better surface finish as compared to traditional shot peening process [3].

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Deep cold rolling is a process whereby a hydrostatically controlled ball or roller is applied onto the material surface under a controlled pressure. The rolling pressure causes a small amount plastic deformation on the surface and sub-surface area, inducing a deep layer of compressive residual stress. The working principles of the process are shown in Fig. 1. Although deep cold rolling is more cost efficient as compared to conventional shot peening and laser shock peening, one of the challenges in adopting deep cold rolling is its limitation in applying to different geometrical profiles on aero-engine components, especially components with thin and intricate features (small radii and fillet) around areas with low tool accessibility.

In this study, we examine the effectiveness of several deep cold rolling tools in treating different geometrical features of an aero engine component. Experiments were carried out on representative Titanium (Ti 6Al-4V) test coupons of different features to investigate the effects of different process variables on the residual stress profiles.

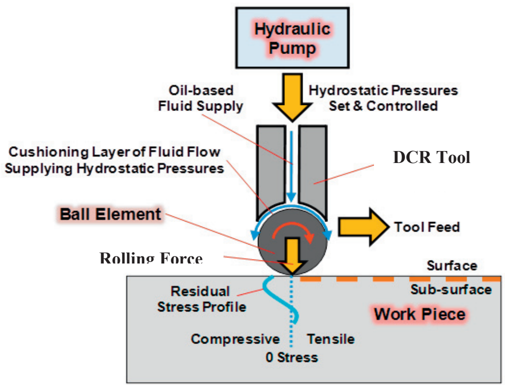

Fig. 1. Working principles of deep cold rolling process.

2. Experimental Methodology

2.1. Equipment

To carry out the deep cold rolling experiments, an ABB robot was selected as the machine platform. Three different types of deep cold rolling tools, as shown in Fig. 2 were investigated to study its feasibility on the output such as residual stress profiles. The tools were attached to the end-effector of the robot with special designed fixtures and cold rolling tool path was programmed according to the profile of the features on the test coupons as well as the required overlap (or 'coverage').

Fig. 2. Equipment set-up for deep cold rolling process on an ABB robotic platform.

2.2. Materials & Test Samples

In this study, Titanium (Ti 6Al-4V) was chosen as the material to be studied and three test coupons were designed and fabricated representing the profiles of the different features of an aero engine component. The design of the test coupons are shown in Fig. 3, 4 and 5 with respective surfaces to be cold rolled highlighted. For processing features on test coupon 1 and 2 (shown in Fig.3 and 4), the single roller and the caliper ball tool was used respectively. For test coupon 3, two flat surface coupons were adopted to represent a particular corner feature for cold rolling using the double roller tool as shown in Fig.5.

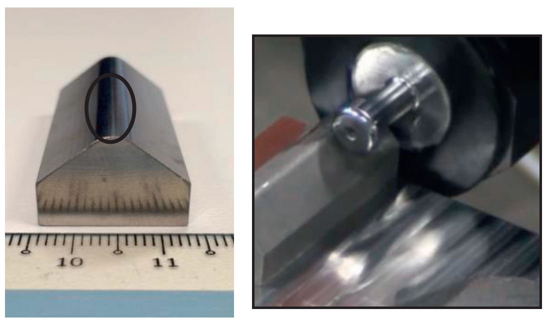

Fig. 3. Test coupon 1 used with a single roller tool

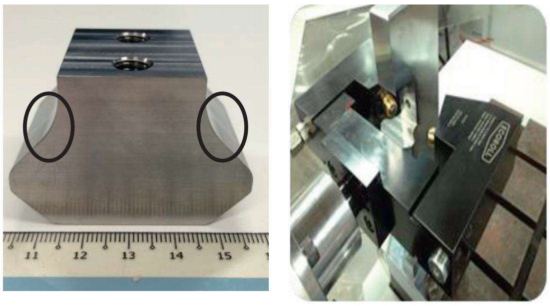

Fig. 4. Test coupon 2 used with a caliper ball tool.

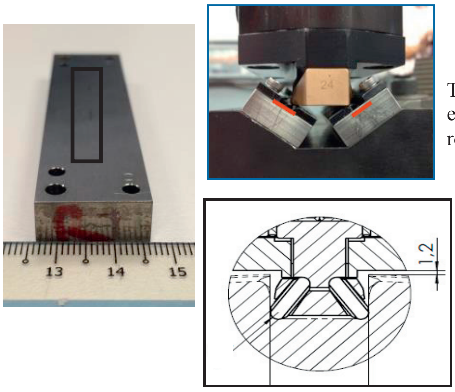

Fig. 5. Test coupon 3 used with a double roller tool.

2.3. Measurements

To quantifiy the level of residual stress induced after the deep cold rolling process, the X-Ray Diffractometer (XRD) and Central Hole Drilling (CHD) method were adopted. For XRD method, the residual stress profiles were obtained by repeating the X-ray measurements and chemical etching alternately.

3. Results and Discussion

Fig 6 and 7 show the cold rolled test coupons and the comparison of the residual stress profiles obtained for the featured test coupons using the three selected tools. The experiments are conducted at the same pressure for the 3 different tool designs. From the residual stress profiles, it can be seen that by using the appropriate process parameters with the correct tool path program on the features, the depth of influence of the compressive residual stress can be quite substantial for the three different tool designs on the different test coupon features, remaining in compression at between 300-700 MPa at 1mm depth. In particular, it can also be seen from the plot that the single roller and caliper ball tool generated a much higher surface compressive stress as compared to the double roller tool. This big difference in the induced surface compressive residual stress between the tools might be due to the difference in the tool contact surface area resulting from the geometry of the roller and ball type tool. A larger tool contact surface area tend to induce a higher level of plastic deformation on the material.

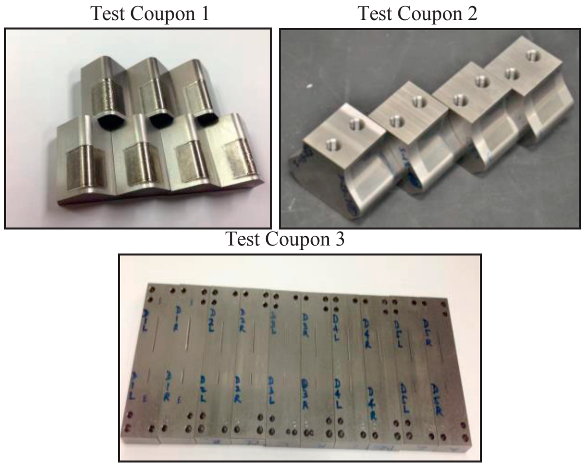

Fig. 6. Cold rolled test coupons.

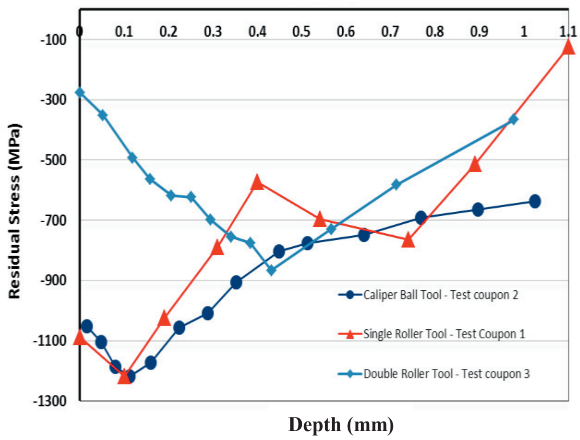

Fig.7. Residual stress profiles measured for test coupon 1, 2 and 3 using different tool designs.

In order to gain a better understanding on the effect of process variables (i.e. pressure, overlap and feed rate) on residual stress, experiments were conducted for the caliper ball tool on test coupon 2.

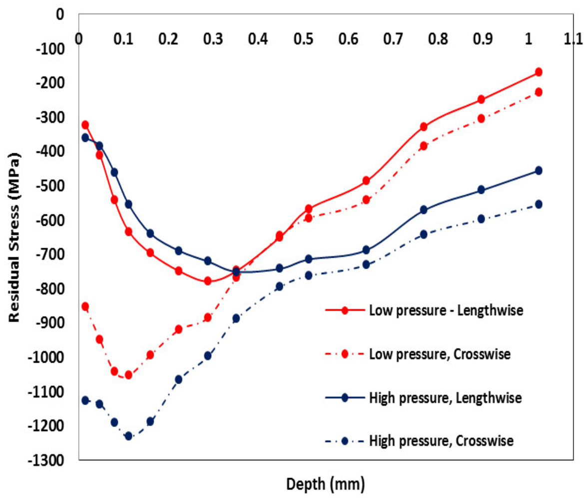

Fig. 8. Effect of deep cold rolling pressure on residual stress profile in lengthwise and crosswise direction.

Fig.6 shows the residual stress profile after deep cold rolling with two different pressures (i.e. high and low). The experimental plots clearly revealed that for this caliper ball tool, much higher surface compressive residual stress was generated in the crosswise direction as compared to the lengthwise direction. Lengthwise direction is the rolling direction of the tool while crosswise is at 90 degrees to the lengthwise direction. In addition, it can also be seen that crosswise direction also shown significantly high compressive residual stress in the sub surface region up to a depth of about 0.4mm. After 0.4mm, the stress reduced quite significantly, moving towards the tensile direction and approaching to almost the same level as in the lengthwise direction. Comparing the difference between the applied rolling pressure, it is interesting to note that the influence is only significant again after 0.4mm where the higher pressure appeared to have a more pronounced effect , especially at 1mm depth where the compressive residual stress is significantly higher.

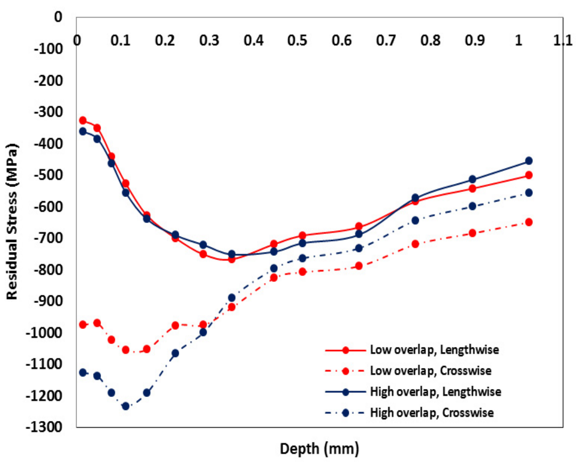

Fig. 9. Effect of overlap on residual stress profile in lengthwise and crosswise direction.

Figure 7 shows the residual profile after deep cold rolling with two different overlap (i.e. high and low). Overlap is defined as the amount of coverage by the rolling ball on a specified cold rolling surface. From the results, it can be seen that overlap only had a slight influence in the residual stress profiles in the crosswise direction and had almost no influence in the length wise direction. Similar to the influence of rolling pressure, the measurement results showed much high values both on the surface and sub-surface regions in terms of compressive residual stress.

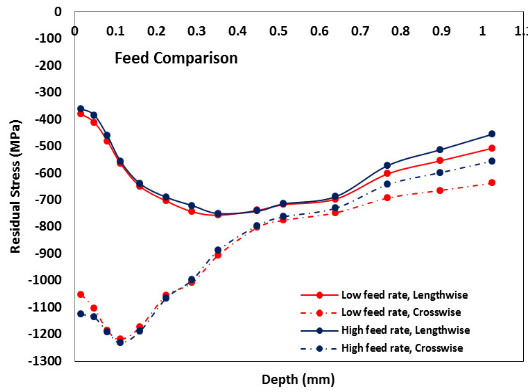

Fig.10. Effect of feed rate on residual stress profile in lengthwise and crosswise direction.

With regards to feed rate, similar phenomenon was observed from the plot shown in Fig. 8 where feed rate (both high and low) shown completely no influence in the residual stress profiles.

4. Conclusions

In order to expand the application of deep cold rolling process in aero engine manufacturing, this study investigated the feasibility of three types of deep cold rolling tool design on three selected features design on test coupons using a robotic platform. With the right tool path program and proper selection of process parameters, the results shown that fairly high compressive residual stress in the sub-surface regions can be generated on the features using the selected tools. In addition, this work also proved that a robotic platform can be consider as a viable alternative to 5-axis CNC machine which is usually considered when running deep cold rolling process.

With regards to gaining a better understanding on deep cold rolling process variables, this study shows that for a ball geometry tool, compressive residual stress measured is consistently larger in the crosswise direction for the process variables considered in this work. In addition, varying the overlap (or cold rolling coverage area) and the feed rate do not have much influence to the compressive residual stress profiles in both measured direction. Significant influence in the profiles was observed by changing the rolling pressure especially at the surface at the sub surface region but starts to move in the tensile direction after this depth. As such, rolling pressure should be investigated and studied in more detail in designing a deep cold rolling process for a specific feature as this will not influence the mechanical properties of the part. Another important point to consider is since deep cold rolling essentially induced plastic deformation by material deformation, local distortion around intricate features should also be studied as this small level of distortion may affect the geometry of the feature and may also lead to high stress concentration around it.

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