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Residual Stress Evolution During the Manufacturing of an Aircraft Component

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Abstract. This paper proposes a comprehensive analysis of the evolution of the surface residual stress state over the manufacturing stages of generic forged aircraft components. This has been achieved through an experimental procedure, involving forging of the generic component preforms, heat treatments, and machining operations on Computer Numerical Control milling and lathe centers. Surface residual stresses were measured using X-ray diffraction technique. The results showed a high scatter of surface residual stress measured in the same zone although the machining was done by the same cutting tool and under the same machining conditions. This suggests that the residual stress measured at a specific zone is significantly sensitive to previous and further major material removal such as rough pocketing the components have underwent. Moreover, it was found that the quenching and aging heat treatment drastically modify, not only the machining induced-residual stress state, but also the physical surface characteristics as demonstrated by the shear to normal residual stress ratio and the full width at half maximum of the X-ray diffraction peaks. Conclusively, the findings of this work help both researchers and manufacturers to better understand the challenges related to the design and the manufacturing of structural aircraft components made from forgings.

Keywords. machining, residual stress, forging, heat treatments, aeronautical aluminum alloy

1. Introduction

Structural aircraft components are commonly manufactured from stocks processed by rolling (plates) or forging (preform). These components are often exposed to distortion induced by residual stress relaxation. The distortion is a tremendous manufacturing challenge, causing non-conformance, rework and delays with an estimated cost of 290 million dollars referring to a study by Boeing [1, 2]. Several studies have been conducted to investigate the residual stress evolution (or relaxation) and the resulting distortion of

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aircraft components during and after the manufacturing [3]. While most of the previous research studies [4, 5] investigated thin-walled parts manufactured from rolled plates without considering the effect of inherent residual stresses [3], few of them have focused on the machining of aircraft components from forged blanks or preforms [1, 2, 6]. Besides, most of these studies have explored airframe components with simple geometries where less attention has been given to the effect of intermediate heat treatment and machining operations involved in the manufacturing workflow of these components. Nevertheless, structural landing gears components like struts have complex non-symmetric geometries and require specific surface integrity and functional characteristics (wear, contact, fatigue, corrosion) along with high mechanical strength and uniformly distributed microstructure. Moreover, the manufacturing of these components requires a meticulous strategy including forging, heat treatments, deep drilling, boring, milling, superfinishing or surface treatment and painting. Usually, most of the material removal is carried out during drilling of cylinders and the rough pocket milling. Therefore, this paper aims to provide a comprehensive analysis of residual stress state evolution after critical manufacturing stages like drilling, pocketing and heat treatments of forged large landing gear components.

2. Experiment

2.1. Work Material

The work material is the 7175-aluminum alloy which is often used to manufacture several aircraft components such as struts and brackets of landing gear where high strength combined with stress–corrosion cracking resistance are required. Its nominal chemical composition is given in Table 1.

Table 1. Nominal Chemical Compositions of 7175 Aluminum Alloy

Element	Zn	Mg	Fe	Cu	Cr
%wt.	5.47	2.45	2.23	1.52	0.2
Element	Si	Mn	Ti	Ca	Mo
%wt.	0.14	0.13	0.043	0.002	0.000

2.2. Forging Process

Generic components (Figure 1a) were closed die forged on 230 tonnes hydraulic press at a temperature of 400°C, followed by a room temperature quenching. These forgings have total dimensions of 123.7 mm length, 101.8 mm width, and 40.1 mm height.

2.3. Machining Process

The machining of generic forged parts was carried out on CNC turning lathe and CNC vertical milling center. The machining strategy involved several machining operations, including drilling, boring, and milling (Figure 1b). The machining conditions are displayed in Table 2.

Table 2 Machining sequence and equipment

Machining sequence	Machine-tool	Cutting tools
Stage 1: General rough milling (GRM)	Frayar TR-60 CNC milling center	End mill AADE0500J3BRC
Stage 2: Drilling (D)	Mori Seiki SL-25M CNC lathe	holder: DFT1000R2SSF150 Insert: DFT05T308HP
Stage 3: Rough boring (RB)	Mori Seiki SL-25M CNC lathe	Boring bar: A12SSCFPR3 Insert: CPGT325 HP
Stage 4: Rough pocketing (RP)	Frayar TR-60 CNC milling center	End mill AADE0500J3BRC

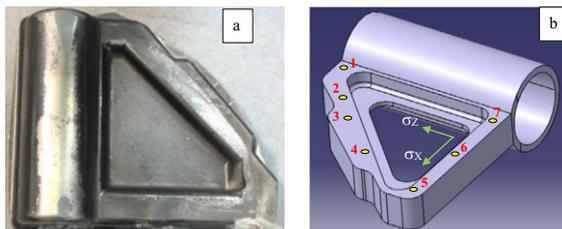


Figure 1 Generic component after (a) forging and (b) machining.

2.4. Heat Treatments

After rough pocketing (Stage 4 – see Table 2), the machined parts undergo a solution heat treatment at 470 °C for 2.5h followed by a quenching in a water. Then, the parts were artificially aged at 107 °C for 4h and at 177 °C for 24h to achieve T74 conditions (Stage 5).

2.5. Residual Stress Measurement

The residual stresses were measured after rough boring (Stage 3), rough pocketing (stage 4) and heat treatments (stage 5) at seven (7) locations as illustrated in Figure 1b. To this end, an X-ray stress analyser type μ -X360, developed by Pulstec Industrial Co is used for measuring normal (σ_z, σ_x) and shear (τ_{zx}) residual stresses (Figure 1b). The μ -X360 stress analyser uses $\cos\alpha$ method and 2D detector allowing the measuring residual stresses and the full width at half maximum (FWHM) of the diffraction peaks.

3. Results and Discussion

As previously mentioned, the manufacturing strategy of the forged component includes several steps. In the present paper, special attention is given to the residual stress state after rough boring (RB), rough pocketing (RP) and quenching/ageing (QA) heat treatment. That is the surface of interest in this study has only been machined during the general rough milling (GRM). The objective is to analyze the effects of major material removal and possible residual stress redistribution on the evolution of the surface residual stress. Figures 2 and 3 depict, consecutively, the surface residual stresses in Z (σ_z) and X (σ_x) directions. It can be seen from these figures that normal residual stresses values and trend obtained after rough boring and rough pocketing are very similar. Besides, σ_x stress experiences higher absolute values and variation, ranging from -5 MPa to 80MPa after RP and from 17MPa to 70MPa after RB. It seems that the residual stress

redistribution induced by the material removal during the RP wasn't enough intense to influences the residual stress state at the surface. This can be explained by the fact that forging introduces low residual stress gradient [6] that is not sufficient to introduce significant changes in surface residual stresses, considering the high stiffness of the part at the beginning of the manufacturing process. The variation of the residual stress over the analysed surface can be attributed to the change of the tool path regarding the fixed coordinate system related to the machined component (Z, X) and the scatter of the residual stress distribution induced by the forging step.

Conversely, QA heat treatments significantly influence the residual stress state at the surface as shown in Figures 2 and 3 The residual stress state has shifted from tensile to highly compressive. This result is in agreement with [7]. In fact, during quenching the cooling rate at the surface is faster than that of the bulk, resulting in larger plastic deformation at the surface layers compared to the bulk material of the component which favoring the formation of a compressive residual stresses at the surface and tensile at the bulk. T74 aging heat treatment slightly reduces the residual stress generated by the quenching, but it still compressive as confirmed by [8]. Figures 2 and 3 also show significant variation in the average residual stresses values after QA, ranging between -59 MPa and -140 MPa for σ_x , and between -71 MPa and -135 MPa for σ_z . Moreover, σ_z and σ_x values follow an opposite trend, that is σ_z reaches its maximum value around location 5, which corresponds to the location of the minimum value for σ_x . Interestingly, residual stress values at positions 1 and 7 were found to be similar for each measurement direction (Z and X). This can be explained by the residual stress redistribution after heat treatment which is function of the geometry and dimensions of component's section. For example, the part's sections at location 1 and 7 have roughly similar areas and both are constrained with the main cylinder (Figure 1b). So, it's expected that these zones behave similarly during the heat treatments and then generating a similar residual stress distribution. Position 5, on the other hand, is the furthest measurement location from the main cylinder and the less constrained, having the weakest stiffness. Hence, this zone is the most sensitive to the variation of the residual stress distribution immanent to QA.

Normal residual stresses are often accompanied with shear residual stresses in the machined surface layer [9]. Figure 4 shows significant shear stress (τ_{zx}) values and variations after RB and RP. The shears stress for RB and RP follows a parabolic trend over the measurement zone while a random distribution is observed in the case of QA. To discriminate the residual stress state after each manufacturing step, the shear to normal residual stress (τ_{zx}/σ_z) ratio is calculated and displayed in Figure 5. Interestingly, high τ_{zx}/σ_z ratios are obtained after RB and RP where the median values are, respectively, equal to 1:1.3 and 1:2. This result agrees with [10], attesting that the cutting process is the results of the combined effect of shearing and compression loads. The decrease of the τ_{zx}/σ_z ratio after RP is surprising since the Surface A doesn't undergo any machining between RB and RP, suggesting that the residual stress redistribution after high material removal can be a potential influencer in this regard. Moreover, a further reduction of the median value of τ_{zx}/σ_z ratio is recorded after QA (1:7.7), confirming a consequential change in the residual stress state and its formation mechanisms.

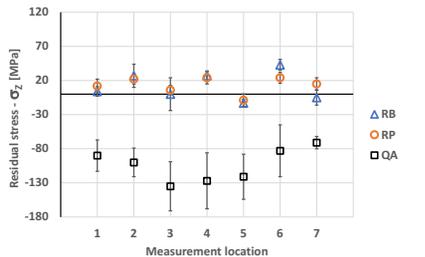


Figure 2 Normal surface residual stress in the Z direction.

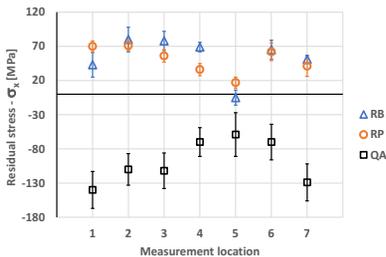


Figure 3 Normal surface residual stress in the X direction.

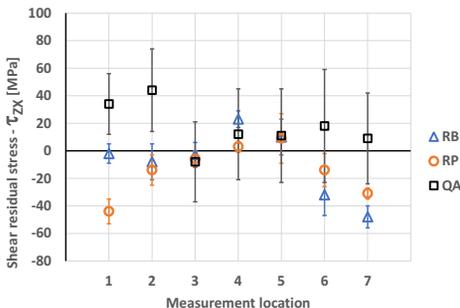


Figure 4. Shear surface residual stress.

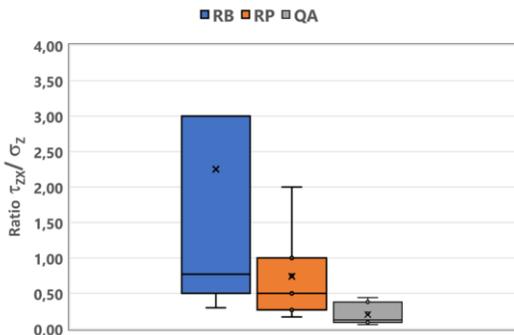


Figure 5. Shear to normal stress ratio after RB, RP, and QA.

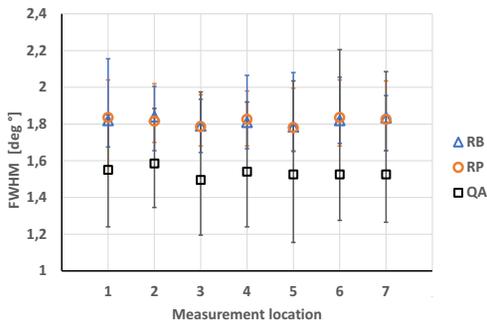


Figure 6 Full width at half maximum (FWHM) after manufacturing steps.

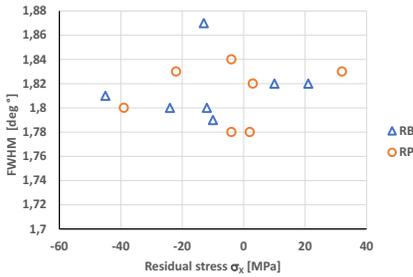


Figure 7 Correlation between FWHM and σ_z for RB and RP conditions.

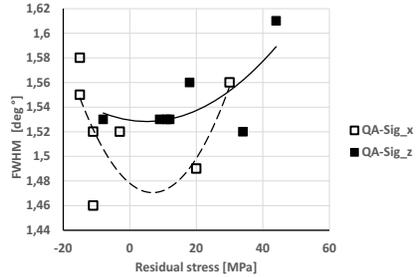


Figure 8 Correlation between FWHM and residual stress for QA condition.

To better understand the residual stress formation after the studied manufacturing steps, the full width at half maximum (FWHM) of diffracted XRD peaks is analysed. As can be seen in Figure 6, FWHM measured after RB and RP are similar and uniformly distributed over the measurement zone. Furthermore, the average FWHM values are higher for RB and RP (1.81°) as compared to QA (1.53°). These results show again that QA step introduces significant changes not only on the residual stress state but also on the surface physical characteristic since the FWHM is very sensitive to mechanical, microstructural and metallurgical conditions of the material [10, 11]. In fact, the no correlation between FWHM and normal residual stresses for RB and RP conditions (Figure 7) suggests that more than one phenomenon has contributed to the formation of the surface residual stresses as stated by [11]. Conversely, the nonlinear correlation between the FWHM and normal residual stresses observed in QA condition (Figure 8) prove that QA heat treatments attenuates or at some extents eliminates the mechanical and microstructural changes induced during the machining steps.

4. Conclusions

This research analyzed the evolution of the surface residual stress state over the manufacturing workflow of a generic forged aircraft component. Three specific manufacturing steps including two major material removal by machining (drilling/rough boring, rough pocketing) and heat treatments (quenching and artificial aging) were considered. Based on the results obtained, the following conclusions can be drawn:

- The variation in the tool path direction and the residual stress distribution inherent to forging contribute to generate large scatter of surface residual stress state over the machined surface;
- The machining introduces lower normal residual stresses but high shear to normal residual stress ratios compared to the quenching and artificial aging heat treatments;
- When applied after machining steps, quenching and artificial aging not only modify the residual stress state introduced by the machining but also the physical surface characteristics as demonstrated by the measurements of the full width at half maximum (FWHM) of the diffracted peaks;
- Major material removal contributes to modify surface residual stresses at different zones of the component.

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