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Abstract

Aerospace gear components are required to demonstrate excellent load carrying and endurance characteristics. Case hardened steels are often utilised for these parts. During the manufacturing process of case hardened steel gears residual stresses are developed. The nature and distribution of these stresses are known to have a significant effect on distortion during heat treatment and machining processes. The fatigue performance of a gear subjected to cyclic loading is also strongly dependent on the nature and magnitude of manufacturing induced residual stresses.

In this work the development of residual stress during the heat treatment and machining process has been assessed in case hardened steel alloy spur gears. Gears have been manufactured from two different initial conditions; as-received bar material, and hot forged billet. A spur gear geometry was rough machined prior to full heat treatment, and subsequent surface finishing. The evolution of bulk residual stress distribution within the gears throughout the manufacturing process was measured using the Contour Method. Surface residual stresses, complimentary to contour method, have been measured by X-ray diffraction.

Gears from both manufacturing routes (i.e. machined from forged billet and as received bar) were found to develop tensile residual stress in the core of the gear following full heat treatment. High compressive stressed regions develop at the carburised case region at the exterior of the gear. The final residual stress magnitude and distribution within the gear was found to be independent of the initial forming process.

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Residual Stresses in Case Hardened Steel Gears

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Introduction

Gears are typically subjected to high levels of cyclic loading and stresses in service, and as such are susceptible to fatigue failure [1]. Forging of gears and gear blanks has been shown to have the potential to improve mechanical properties such as impact toughness and fatigue strength [2]. Fatigue of gears is typically initiated at the site of inclusions in the region of the maximum bending stress [1]. Inclusions, or macrosegregations, can be broken down by the forging process and this has the potential to improve fatigue performance. Additionally, forging can influence the flow lines of microsegregations which can enhance or detrimentally affect fatigue performance depending on orientation [3]. Navas found that the effects of forging on microsegregation structures can remain even after normalizing heat treatment [4]. The effect is heterogeneity in the distributions of hardness and residual stress distribution.

In addition to microstructural features, residual stresses are a dominant factor in the fatigue performance of gear components [5, 6]. Compressive residual stresses can reduce the effective stress experienced in the gear tooth under a tensile applied bending stress. A number of studies have been conducted to investigate the residual stress state of gears. Particular attention is paid to the effect of surface treatments such as peening [7-9], induction hardening [5, 10, 11] and heat treatment [12, 13] on the resulting residual stress state of the gear.

Residual stresses also play a significant role in distortion of gears during manufacture and operation [10, 14, 15]. The forming route, i.e. hot forging, was shown to have an effect on the distortion behaviour of the S156 steel considered in this work [16].

It is therefore important to distinguish between the effects of residual stress and the effects that forging can have on the microstructure of a gear steel when considering fatigue performance of a gear. In the current work gears have been manufactured from two processing routes; machined directly from as-supplied bar stock, and machined from a hot forged "pancake" gear blank. The residual stress evolution from the initial condition through the entire manufacturing process to a fully machined, heat treated and surface treated condition has been investigated for both forming routes. The effects of forming route on the fatigue performance of gears shall be presented in a future work.

Residual stresses have been assessed using two methods; X-ray diffraction (XRD) and Contour Method. XRD measurement in conjunction with eletropolishing layer removal provides residual stress from the surface of the gear tooth to a shallow depth into the part (i.e. near surface). Contour Method provides residual stress magnitudes and distributions across a section of the gear from the tip of the tooth to the inner bore. By adopting two measurement methods, a clear understanding of residual stress evolution during manufacture and the difference in stress states between forming routes can be obtained.

Experimental Methods

Gear Manufacture

Gears were manufactured using two manufacturing routes; machined from bar stock and machined from a hot-forged pancake. All gears were manufactured from S156 martensitic steel with nominal composition shown in Table 1. The S156 steel bar was supplied in the hot extruded, normalised and annealed condition.

Table 1 – S156 alloy composition

Fe	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al
Bal	0.155	0.19	0.39	0.007	0.0007	1.16	0.23	3.95	0.09	0.014

Forging was performed at the AFRC using a Schuler AG 2100 tonne screw press. Forging preforms were heated in a protective gas furnace at 1050°C prior to transfer to the screw press die. A forging reduction of at least 50% was implemented to ensure further break-up of macro segregations that can be present in the as-received bar stock.

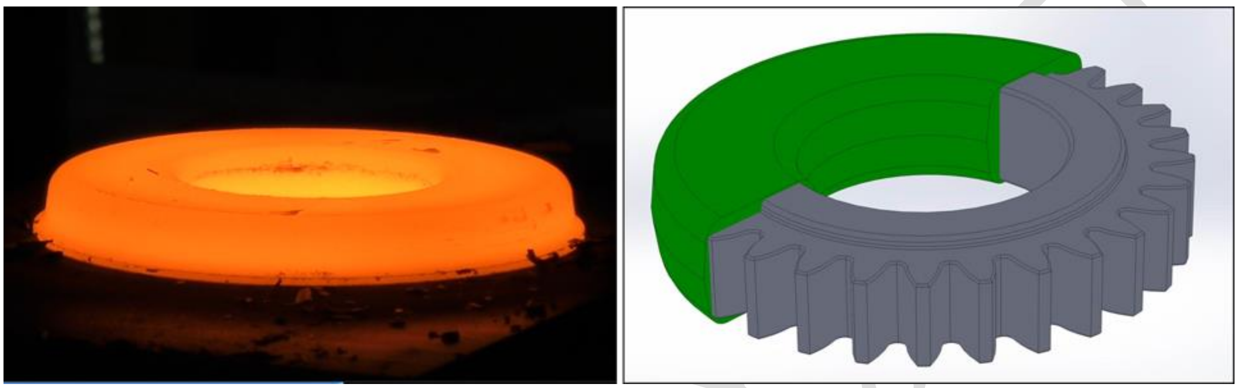

Figure 1 - Pancake forged test gear

The forged pancake, and resulting gear profile following machining, is shown in Figure 1. The gear geometry was selected by NUDU to be suitable for single tooth bending fatigue testing (results not presented here). The gear comprises an outer diameter of approximately 120mm, with a 10mm tooth height.

The gears were machined close to the final geometry, with 0.2mm stock remaining to be removed at the final machining stage. The parts were then heat treated as shown in Table 2. Gears from both manufacturing route (forged & bar) were heat treated together to ensure no batch variability. Normalising and subsequent annealing was performed to relieve residual stresses induced by the forging process.

Table 2 - Heat treatment schedule for S156 steel

Step	Heat treatment	Temperature
1	Normalise	920°C
2	Anneal	650°C
3	Carburising	900°C
4	Annealing	650°C
5	Hardening (Oil Quench)	820°C
6	Sub-zero	-70°C
7	Tempering	250°C

The gears were final machined after completion of the heat treatment cycle. Shot peening was then applied using a dual shot process. Finally, superfinishing was conducted to prepare the gears for testing.

X-ray Diffraction Residual Stress Measurement

Surface and near-surface residual stresses were measured at NUDU using XRD and eletro-chemical polishing layer removal. A Stresstech Xstress 3000 diffractometer was used for all measurements reported. All of the measurements were carried out at mid-facewidth and as close as practicably possible to the 30° tangent point in the root fillet (i.e. the point of maximum bending stress during testing). A 0.8mm aperture size was used. Table 3 details the parameters used for XRD measurements.

The gear tooth was masked leaving the measurement location exposed. Material was removed incrementally using electro-chemical polishing. XRD residual stress measurement was conducted after each material removal stage. Stresses were measured in two principal directions: the direction running across the facewidth (lead), and root to tip direction (profile). The orientation of the measured stress directions can be seen in Figure 5.

Table 3 - X-ray diffraction residual stress measurement parameters

Diffractometer	Stresstech Xstress 3000 G2R
Radiation Source	Cr-Kα
Wavelength	0.2291nm
Measurement Method	$\sin^2\Psi$
Miller Indices (hkl)	211
Elastic Modulus	211 GPa
Poisson's Ratio	0.3

Contour Method Residual Stress Measurement

The Contour Method residual stress measurement technique was introduced by Prime [17] as a convenient means of measuring 2D map of residual stress across an entire section of a part, in the out of plane of the cut direction. Based on Bueckners superposition principle [18], the original residual stresses in a part can be determined from the elastic strain required to force a cut surface back to plane conditions following electric discharge machine (EDM) cutting (Figure 2).

In a stress free part the surface displacement following EDM cutting will be zero. In a stressed component, elastic relaxation of residual stresses causes surface displacements. The cut surface topography is measured using a Coordinate Measuring Machine (CMM). Surface fitting techniques are applied to the measured topography. The surface topography is then applied as boundary conditions in a finite element analysis (FEA) to calculate the original residual stress in the gear.

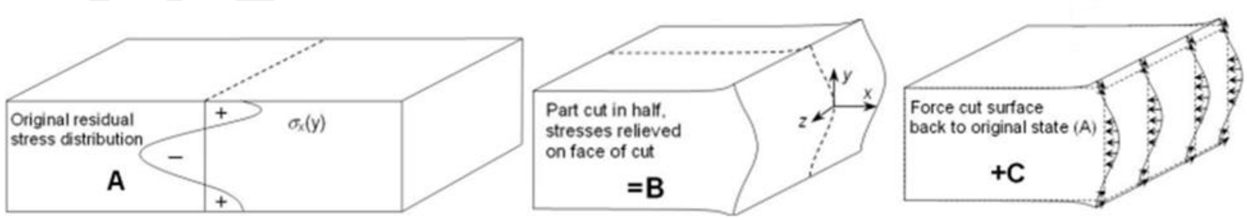

Figure 2 - Principles of Contour Method residual stress measurement [19]

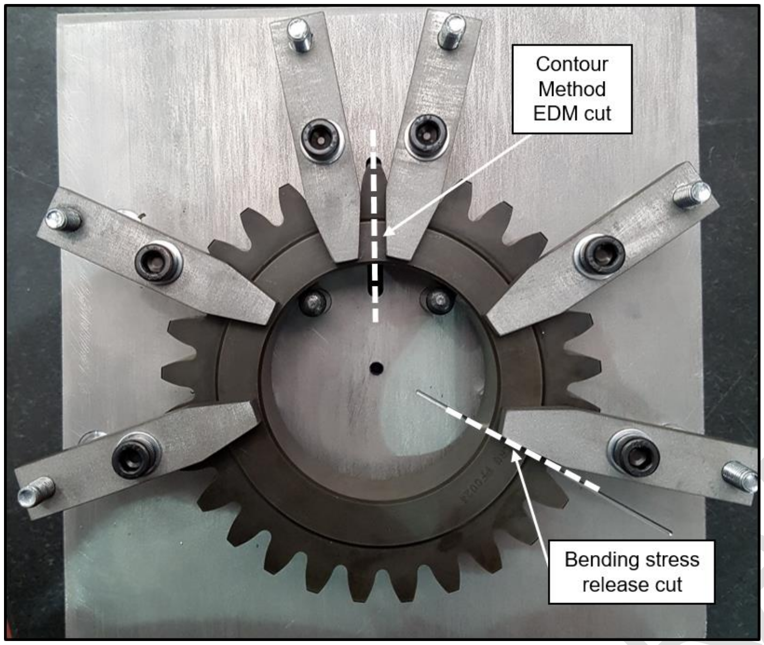

Figure 3 - Fixturing and EDM cut locations for Contour Method

A multiple step cutting strategy was adopted for the EDM sectioning portion of the Contour Method. In a cylindrical component with a bore, such as the gear considered here, the presence of hoop stresses can cause the part to distort during sectioning. To account for the relaxation of these stresses, an initial “opening” cut is made. A line was scribed parallel to the cutting plane 5mm either side of the EDM wire path.

After cutting is completed the clamping is released and the part is free to move due to stress relaxation. The measured relaxation induced movement is then combined analytically with the Contour Method results to determine the true stress state [20]. Following the hoop stress release cut the part is sectioned using cutting/clamping conditions suitable for Contour Method analysis. The location of both cuts are shown in Figure 3.

In this instance, minimal movement was observed during hoop stress release (<0.5mm). Therefore the Contour Method calculation is taken to be a true representation of the stress state without the requirement for hoop stresses.

The success of a Contour Method residual stress measurement is highly dependent on minimizing bulk movement of the part and development of localized plasticity at the tip of the cut during cutting [21, 22]. A bespoke clamping fixture (Figure 3) was developed to mitigate against bulk movement and localized plasticity developing. EDM cutting was performed using an Agie Charmilles wire EDM with 0.25mm diameter brass wire. “Skim cut” settings were used to achieve the best possible cut and minimize errors in the resulting surface topography.

The location chosen for Contour Method analysis was from the tip of the tooth through to the inner bore, with the out of plane stresses measured being the hoop component of stress. Although bending fatigue failure of the gears occurs generally at the root, assessing this location by Contour Method is difficult due to the small area of material in the root location. Therefore to get the highest quality results for purpose of comparison between manufacturing routes and residual stress evolution throughout the manufacturing process, the tip-inner bore approach was chosen as most appropriate.

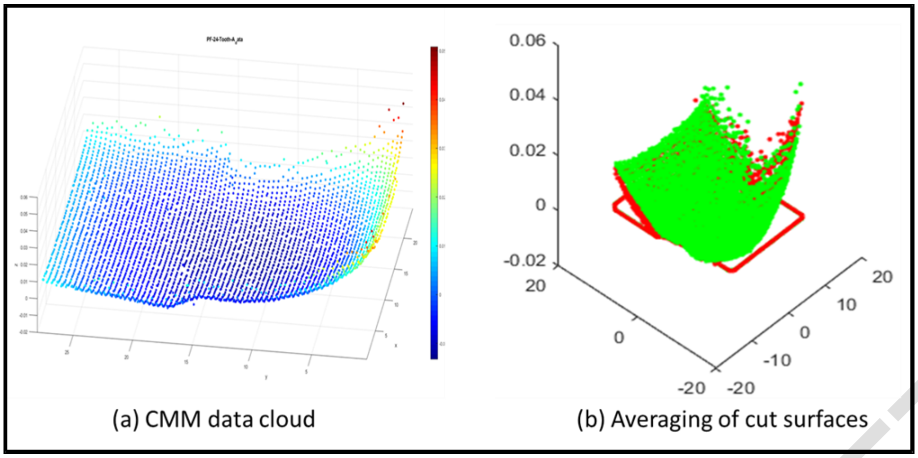

Figure 4 - Surface topography of gear surface following Contour Method EDM sectioning

Following EDM sectioning the two cut faces of each gear were measured by Coordinate Measuring Machine (CMM). A Mitutoyo Crystal Apex C CMM was used with a 1 mm diameter ruby attached to a Renishaw PH10T probe. A point density of 0.4mm x 0.4mm in the x and y directions was measured on the cut surfaces.

The measured surface topographies of each of the two cut faces were then analysed using a series of Matlab codes. The data cloud for each face was cleaned to remove erroneous points, before aligning the two faces. This removes a number of potential error sources by averaging away effects like a non-straight cut. A surface fitting algorithm was then used to evaluate the averaged cut surface. The output of the surface fitting was then used as an input into an FE simulation, where the original residual stresses within the gear are calculated. The data cloud captured by CMM measurement of the sectioned face of a gear is shown in Figure 4.

FEA calculation of residual stress from the measured surface contours was performed using ABAQUS commercial software. A fully elastic model is used (Contour Method is dependent on purely elastic relaxation [17]). The geometry of the sample was modelled as an extrusion of the cut face. Quadratic tetrahedral elements were used with an average element size of 0.4 mm on the cut surface. The model contained approximately 60,000 elements.

Results and Discussion

XRD results

The residual stresses as measured by XRD for the forged and machined from bar gears are shown in Figure 5. Results for forged gears are shown in red, with bar gears in black. Residual stresses in the profile direction (root to tip) and lead direction (across the face width) are presented. The approximate measurement location is identified by a cross in Figure 5. Depth profiling was achieved using eletropolishing and etching, starting in 10μm increments close to the surface, with increment size increasing with depth. This approach provides the richest dataset in the high compressively stressed region most influential on fatigue performance. Residual stress relaxation and redistribution associated with localized electro-chemical polishing have not been accounted for.

The residual stress measurements in Figure 5 are for gears in the final condition (i.e. case hardened, finish machined, shot peened, superfinished). High compressive stresses are expected due to the processing history. Peak compressive stress of 1200MPa is found at a depth of 20μm for the forged gear in the lead direction. The peak compressive stress of the machined from bar gear was 1160MPa at a depth of 40μm (also in the lead direction).

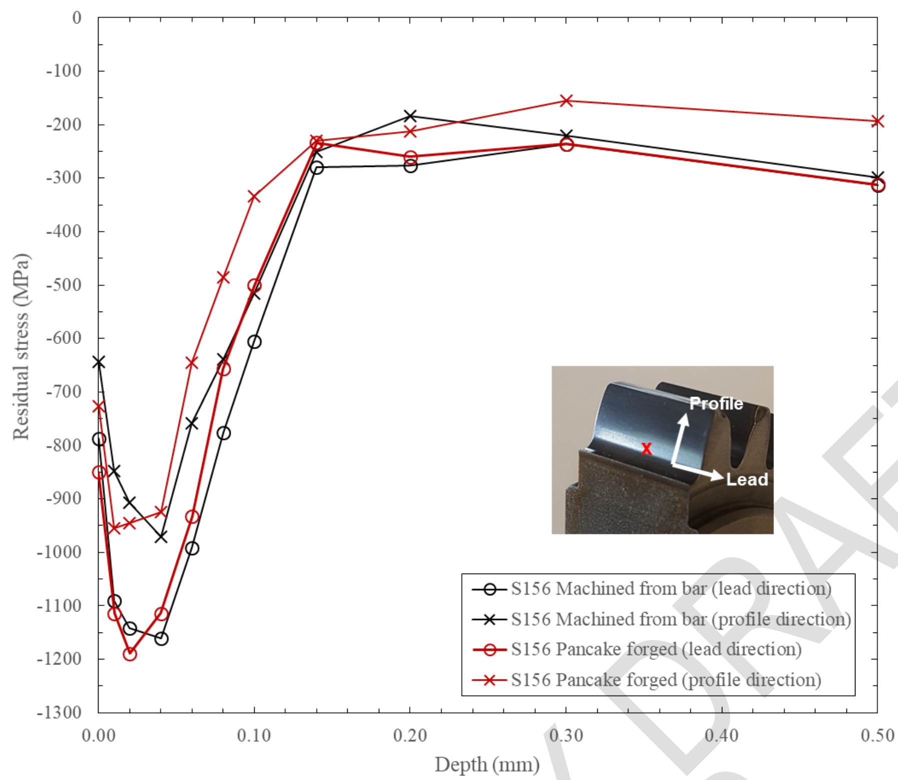

Figure 5 - XRD residual stress measurement results for final condition forged and machined from bar gears. Measurement location close to root of gear (marked “x” in figure)

The results show that for both components of residual stress, the peak stress is closer to the surface for the forged gear as opposed to machined from bar. This could have an effect on the fatigue performance of the gear under bending loads, depending on the location of typical crack initiation. The difference in residual stress profiles could be explained by variability in the case hardening or surface treatment processes. Alternatively, excessive material stock removal during final machining could cause the shift in peak stress position.

Despite the presence of variability between gears of the two manufacturing routes, the magnitude of the variation is not deemed to be significant. A variation of +/- 50MPa and +/-20µm, for stress and peak stress position respectively, falls within the bounds of measurement uncertainty and batch variability.

Contour Method results

Cross sectional maps of residual stress for the two gear manufacturing routes (forged and bar) are presented in Figure 6. Residual stress distributions are shown in the initial condition, i.e. machined from bar or forging, and final conditions. The final condition of the gear refers to after all manufacturing processes; case hardening heat treatment, finish machining, shot peening and super finishing. The surface fitting for the results shown used bivariate splines with 3.5mm knot spacing.

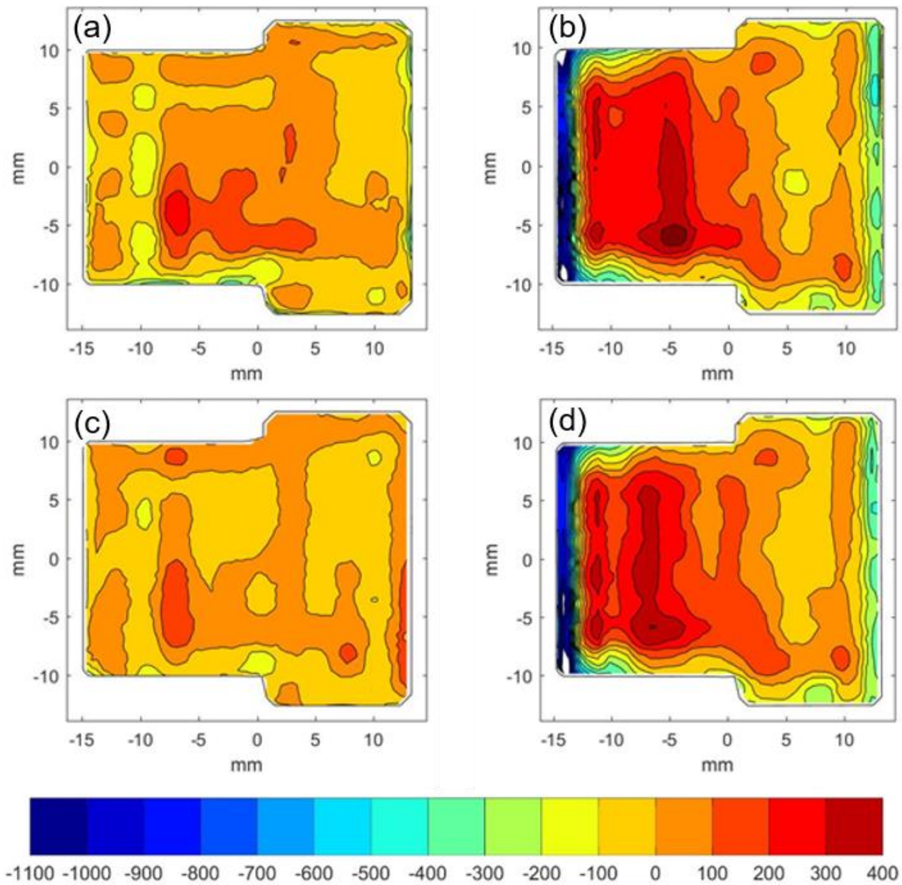

Figure 6 - Cross sectional residual stress maps for (a) Bar - initial condition, (b) Bar - final condition, (c) Pancake forged - initial condition, (d) Pancake forged - final condition

The magnitude of residual stresses are low for both manufacturing routes in the initial condition (Figure 6 (a) and (c)). Maximum out of plane, i.e. hoop, stresses of 100MPa tensile were measured. The supplied bar stock was in the annealed condition so low stresses are expected. The forged pancake cools relatively slowly (air cool) so significant stress gradients are not expected.

The line plots for residual stress from the gear tip to inner bore are shown in Figure 7. Again it can be seen that the gears from both manufacturing routes exhibit low stress magnitudes in the initial condition. The stress distributions are similar for both routes; no significant difference is observed.

The residual stress magnitudes increase significantly by the time the gears have gone through the full manufacturing process. Case hardening induces compressive residual stress in the case layer (approx. 1.1mm) due to the volumetric change caused by carbon addition. During quenching, the compressive residual stress increases further in the case due to differential gradient in cooling, and also phase transformation. Although annealing and tempering are performed, a significant stress profile remains. The final processes of shot peening and superfinishing induce compressive stress at the gear surface locally (primarily as a result of peening).

From Figure 6, a high tensile core of approximately 400MPa is exhibited for both the forged and the machined from bar gears. The tip of the gear for both manufacturing routes experiences compressive residual stresses in the region of 1100MPa. The magnitude of stresses at the gear tip as measured by contour method are comparable with those measured on the surface of the tooth by XRD.

As with the initial condition gears, there is minimal difference observed in residual stress magnitudes and distributions for the final condition gears from both manufacturing routes. Figure 7 shows peak compressive stresses of -1000MPa to -1100MPa within 1mm of the surface. Within the first 1mm of the surface, Contour Method measurements are susceptible to error due to artefacts introduced during the cutting and clamping process [21]. Uncertainty values are not commonly reported for Contour Method results, however an estimation of 10-15% is regarded as appropriate [23]. The variability between forged and machined from bar gears falls within this uncertainty margin.

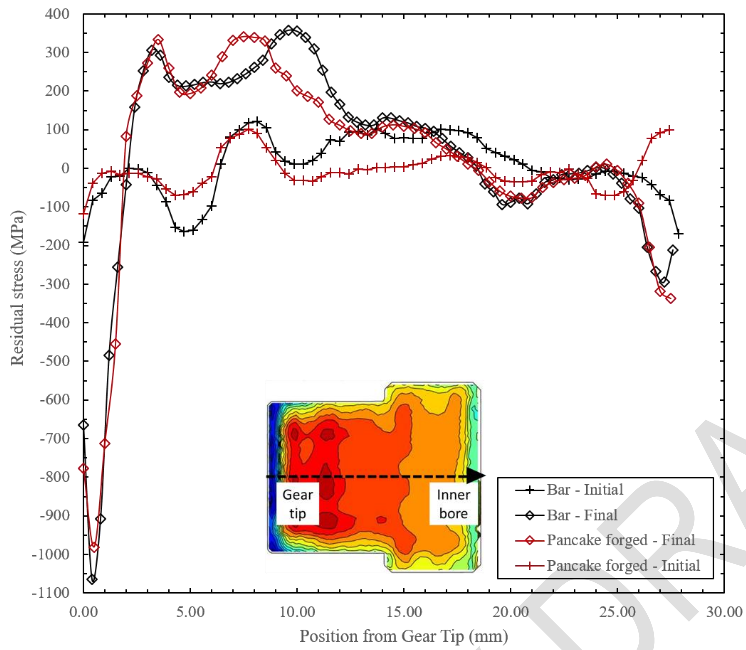

Figure 7 - Line plots of Contour method residual stress measurements - Tip of gear tooth towards inner bore

Discussion

By considering the results of both XRD and Contour Method residual stress measurements, a detailed understanding of the near surface and through thickness residual stress state of the forged and machined from bar gears has been obtained. The difference in residual stress distributions and magnitudes for gears machined from forgings and those machined from bar stock was found to be largely insignificant.

A small variation in the magnitude and location of peak compressive stress in the heat treated, finish machined, shot peened and superfinished gears was observed for the two manufacturing routes. However the difference is small enough to be attributed to measurement uncertainty and general processing variability. For future work considering the fatigue performance of the gears, this variation should be re-addressed should the fracture and fatigue behaviour vary significantly between the two routes.

The Contour Method results show a severe increase in residual stress throughout the manufacturing process. As residual stresses are self-equilibrating across any given principal plane in a body, achieving the desired high compressive strength (for fatigue purposes) close to the surface will result in tensile stresses redistributed within the part. This has the potential to cause distortion issues during further manufacture of the gear or during operation. This issue is unavoidable. A positive output from this work however is that gears from both manufacturing routes exhibit similar bulk residual stress distributions. Therefore a distortion mitigation strategy already in place for conventional, machined from bar gears could be read directly across to forged gears.

Conclusions

- Test gears have been manufactured from S156 case hardened gear steel using two manufacturing processes: machined from bar stock, and machined from pancake forgings.
- Residual stresses in the initial condition (following machining) and final condition (following heat treatment and surface finishing) have been measured using Contour Method technique. Residual

stresses close to the surface of the gear tooth have been assessed using X-ray diffraction with electro-chemical polishing layer removal.

- The difference in residual stress magnitudes and distributions of near surface (XRD) and through thickness (Contour Method) between the two forming routes (forged, bar) was observed to be insignificant. In the case of variation in fatigue performance or distortion behaviour be observed between forged and machined from bar S156 gears, factors other than residual stress should be attributed.
- Contour Method residual stress measurements provided a quick and convenient way of observing residual stress evolution through the manufacturing process, and for comparing between forming routes. Although XRD provides data in areas most critical for fatigue performance, Contour Method was found to be suitable for comparative for the purpose intended here.

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