Effects of Heat Treatment on Residual Stresses induced due to turning operation on Invar-36

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Abstract

Machining is a large strain and high strain-rate deformation process with a complex stress state. This leads to large residual stresses on machined surface and sub-surface. In order to study this, facing operations was performed on fully annealed Invar samples to generate surface and subsurface residual stresses. Surface and subsurface residual stress tensors were measured by performing spot X-Ray Diffraction (XRD) along the depth of the specimen. The process was performed for fixed cutting parameters to generate a residual stress profile and then put through different heat treatment cycles for stress relieving. The nature of residual stress as a function of depth, before and after heat treatment is discussed.

Keywords:Residual Stress, turning, Invar-36, X-ray Diffraction, heat treatment.

1. INTRODUCTION

Invar 36 (which contains Iron and 36% by weight as Nickel), is widely used in industries like aerospace, precision instruments, seismic creep gauges, space equipment etc. due to its low coefficient of thermal expansion and high dimensional stability. Parts made from Invar 36 are usually machined. Machining can produce non-uniform plastic deformation in the component that is machined. Machined components have induced residual stresses which influences its performance during service life. The characteristics that are affected by residual stresses are fatigue life, corrosion resistance and part distortion [2]. Residual stresses can be beneficial as well as harmful. Compressive residual stresses are advantageous as they impede initiation and propagation of fatigue crack and cracking due to stress corrosion [5].

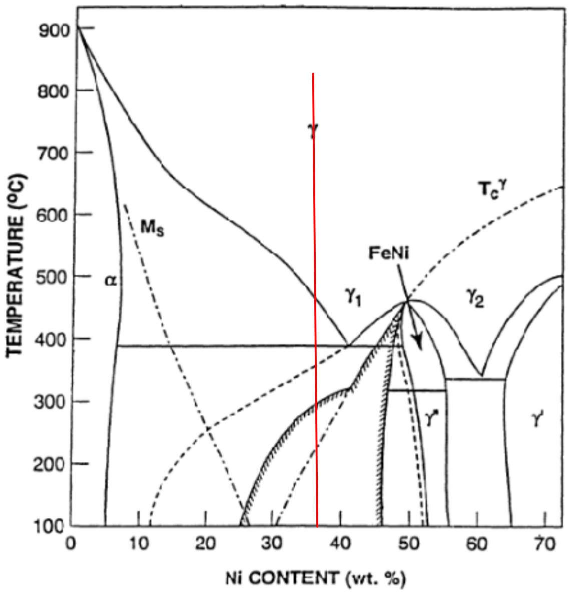

Fig 1. Iron Nickel Phase diagram

The composition of Invar 36 is indicated by the red line on the iron Nickel phase diagram in figure 1. During machining, the workpiece tool interface is expected to reach very high temperatures. If the temperature crosses 500°C, Invar 36 would form a single phase (gamma phase). However due to the coolant, the workpiece will get quenched and is likely to enter the metastable phase region of γ and γ'. This phase transformation would also impart residual stresses due to volumetric changes. Hence, the residual stresses are a combination of the residual stresses due to large plastic deformation imparted during machining and the residual stresses due to phase transformation. However, it should be noted that heat treatment would affect both the residual stresses caused due to large plastic deformation as well as due to phase transformation.

There exists more than 10 different methods for measuring residual stresses. They are broadly divided into two main categories, namely, destructive and non – destructive techniques. The destructive techiniques consist of methods like hole drilling, sectioning, ring core, contour and deep hole. Hole Drilling is the most commonly used destructive measurement technique. The non-destructive techniques include Neutron diffraction method, X-ray diffraction method, ultrasonic method and Barkhausen noise method. Out of these X-Ray diffraction method is the most commonly used method.

Diffraction methods made use of the ability of electromagnetic radiation to measure the distance between atomic planes in crystalline or polycrystalline materials. There is a linear deformation of material in its elastic range when an external mechanical or thermal load is applied. The change in the inter-planar sapcing created due to such external loads can be measured using diffraction methods. Diffraction of electromagnetic waves occurs when the radiation interacts with atoms that are arranged in an array. The diffracted rays are of the same frequency with some being strong emissions in certain orientations while some being weak emissions in other

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orientations. The angles at which strong emisions occur are measured [10].

Using the above mentioned angles, the inter-planar spacing is measured using the Bragg's Law. This is a measurement of strain induced. Bragg's Law is mathematically expressed as :
$n\lambda = 2d \sin\theta$
Where :
n – Positive Integer
λ – Wavelenght of the electromagnetic wave
θ – Scattering Angle
d – Interplanar spacing

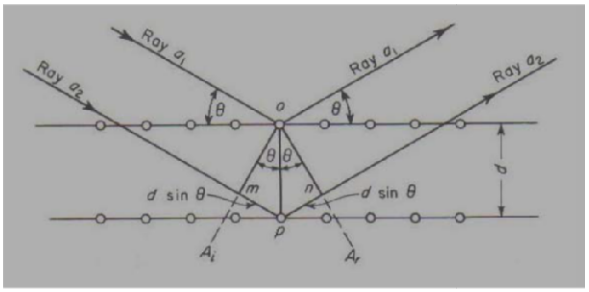

Fig2. Inter-planar spacing using Bragg's Law [13]

Since residual stress has been so essential in understanding the service life of a component, a lot of research work has done on analytical modeling, finite element modeling, to study the effect of machine induced residual stress on certain materials. Matsumoto et al studied the effects of cutting edge geometry and machining parameters on hard turned steel. Their research concluded that tool edge geometry plays an important role in the residual stress profile [11]. Prof. S.G. Kapoor et al. conducted research on machining induced residual stress by modeling and experimentation in annealed AISI 4340 steel [12].There is an analysis done by R.M. Saoubi et. al on residual stresses due to the orthogonal machining on standard and resulfurized SS 316L [4]. Meng Longhui et. al performed measurement of surface residual stresses by turning thin wall Ti6Al4V tubes [3]. However, there is no literature on residual stress studies on turing of Invar -36 alloy. Hence, this work focuses on understanding variation of residual stress as a function of depth in turned invar-36. It also aims at understanding the effectiveness of the stress relieving treatments for the reduction of residual stress.
The sunsequent sections in this paper describe the experimental setup, and results and analysis of the data gathered by performing machining, heat treatment and X-ray diffraction on the machined samples.

2. EXPERIMENTAL SETUP

The material used in this study was hot rolled and annealed Invar -36. The alloy composition and other relevant properties of Invar-36 are given below:

Chemical composition - Fe 62.77%, Ni 36%, Cr 0.25%, C 0.05%.
Hardness - 79 Rockwell Hardness (B)
Coefficient of thermal expansion - 2.03cm/cm °C x 10^{-6} at 150 °C

Machining experiments were performed on a round blank of Invar 36 as per details given below.

Table 1.

Operation	Machine Name	Tool	Cutting Speed (m/min)	Depth of Cut	Feed mm/rev
Turning	EMCO PC Turn	CCMT 0.4	190	0.25	0.1

After completing turning operation, rectangular coupons were cut using wire EDM to perform XRD for residual stress measurements. The coupons were cut in a manner such that there were two perpendicular faces on which the stress measurement could be performed. The two faces were designated as theta phase and radial face as per cylindrical coordinate system. Fig 3 shows the orientation of these faces. The radial face is the face These samples were then used to measure the residual stress on the two faces as a function of distance from the machining surface. Another set of equivalent samples was cut using wire EDM from the turned black. These were subjected to various heat-treatments for stress relieving followed by XRD for residual stress measurements.

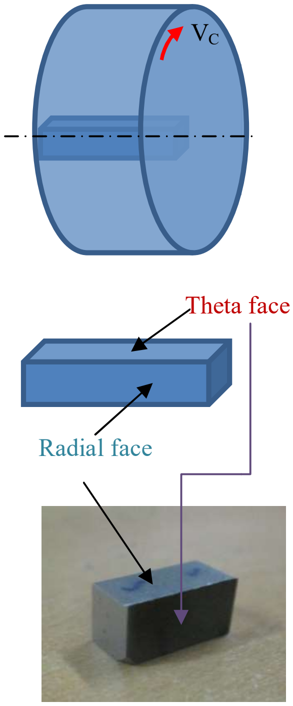

Fig3. Coupon Orientation after wire cut

Table 2 provides details of the heat treatment process performed on the turned sample.
Table 2.

Sample Number	Max Temp	Heating Rate	Cooling Rate

Sample 1	No HT	No HT	No HT
Sample 2	316°C (60 mins)	5°C/min	5°C/min
Sample 3	791°C (60 mins)	5°C/min	5°C/min

XRD for residual stress measurement was performed on Panalytical X-ray machine using a copper anode. The samples were exposed for 3 different ψ (psi) angles and 3 different Ø (Phi) angles. The θ (Theta) angle varied from 5-100 degrees. Standard $\sin^2\psi$ techniques were used to measure the stress and the normal tensorial coordinate transformation methods were applied to calculate the stress tensor.

3. RESULTS AND DISCUSSION

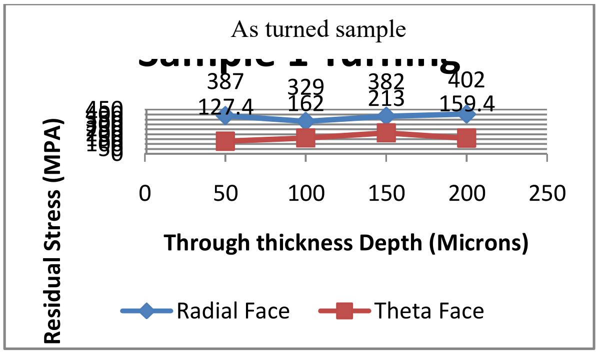

Fig 4. Turned Sample 1 Residual Stress v/s Through thickness depth plot

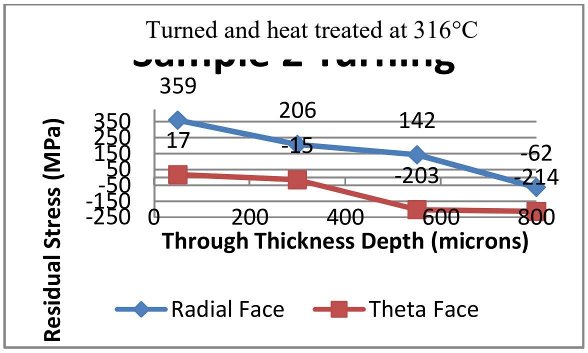

Fig 5. Heat Treated (316°C) Sample 2 Residual Stress v/s Through thickness depth plot

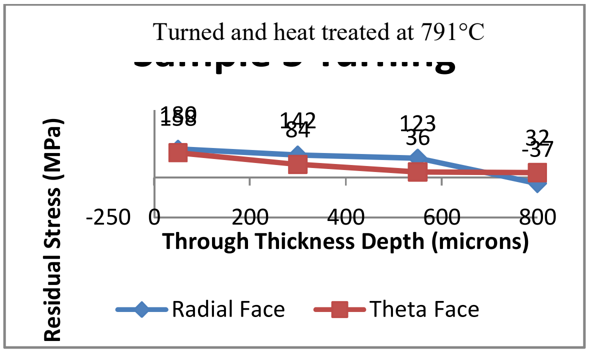

Fig 6. Heat Treated (791°C) Sample 3 Residual Stress v/s Through thickness depth plot

Figure 4 shows the residual stress (Von Mises stress) on the radial and the theta faces of the as turned sample. These are taken at steps of 50 micrometers in the through thickness depth direction. Stresses on both faces are found as tensile, however the magnitude of stresses on the radial face is greater than the stresses on the theta face. Since the total depth to which the measurements were performed is only about 200 micrometers it is seen that the residual stresses remain tensile. Since the overall sample is traction free, it is known that to compensate the tensile stress there will be an equivalent compressive stress in the interior of the sample. However, that has not been measured as the data is only up to 200 micrometers.

Figure 5 shows the residual stresses after performing a heat treatment cycle at 316 °C with 1 hour hold time. These residual stress measurements were performed at larger steps so as to be able to see the compressive stress regime. It is seen that at the surface the residual stresses are tensile in nature and and gradually become negative. In case of the radial face residual stresses, the neutral point is achieved almost at 750 micrometers below the surface. Whereas for the theta face, it is much closer to the surface. It is interesting to see that this heat treatment has led to a drastic reduction in residual stresses along the theta direction; however, it only marginally changed the residual stress along the radial direction.

Figure 6 shows the residual stress distribution as a function of depth after performing a heat treatment at 791°C for an hour. As expected, this being a higher temperature has resulted in reduction of residual stresses on both the radial and the theta faces (as compared to as turned sample of figure 5). However the absolute residual stress in the theta direction, in this case, as compared to Figure 4 shows a higher value. This could be because of internal stress compatibility requirements and needs further investigation.

4. CONCLUSION

From this experiment it can be conclude that the turning operation induces large tensile stresses on Invar-36 alloy surface. By performing heat treatment at a lower temperature of 316°C, these residual stresses on the radial face reduce, however the residual stresses on the theta face do not change a lot. The heat treatment at a higher temperature of 791°C, reduces residual stresses on both the theta and the radial face. More investigations are required to understand the quantitative behavior of the reduction in residual stresses.

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