A Study on Measurement Techniques of Residual Stress in Machining Operations

Aman Rishu, Himanshu Kushwaha, Gaurav Kushwaha, Ajay Goyal

Abstract— Generation of residual stresses on tool and work piece has always been an important issue to determine machinability parameters. These stresses affect, machining to a great extent leading to reduced life of the tool and work piece. These stresses are generated due to cold working, stamping, weld shrinkage, thermal shrinkage etc. There are several methods to measure residual stress. These methods are broadly classified into destructive and non-destructive methods. Also, there is a semi-empirical method recently developed - Eigenstrain Reconstruction Method, which collectively includes the experimental data and Eigenstrain Theory.

In the paper, an attempt has been made to study the methods of determining the quantity of residual stress. Some of the non-destructive techniques are X-ray diffraction method, IR thermal imaging (thermoelastic method) andNeutron Diffraction etc. Study redelivered that all methods are good in various respects but are not favourable in all conditions.

Index Terms— Residual Stress, Non-destructive Methods, Diffraction, Thermoelastic, Eigenstrain.

Fig1. Cracking in the cast aluminium ingot due to excessive residual stress [1].

I. INTRODUCTION

Residual stresses are stresses that retain in the work material after original causes of the stresses have been removed. These

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are induced inside and at the surface of work piece during its processing. Residual stresses are usually undesirable. Unintended residual stresses in a design can lead to plastic deformation or may also cause permanent failure of component. These are developed due to temperature gradient and phase transformations which are generated during machining. Heat from welding may cause localized expansion and thus creating space for the residual stresses [2].

Analysis of residual stresses in the component will also help in determining temperature rise generation at tool and work piece. Not only this, this will also help in selecting optimum cutting parameters for better machinability. Hence, the analysis of the residual stress is a wide area of study and important for modern day materials of work piece and tool. This will not only leads to better machinability but will reduce cost of product by optimizing required power, tool selection and miscellaneous consumption.

The research concerned with evaluating these stress has been listed in the paper in a precise format. This would help in designing engineering components and predicting their lifetime and failure in service. Some of the methods involved in predicting and estimating the amount of residual stress are Diffraction Method, Eigen strain Reconstruction Method, Thermostatic Method and many others.

II. STUDY OF METHODS

A. X-Ray Diffraction Method:

Diffraction methods are based on the ability of electromagnetic radiation to measure the distance between the atomic planes in crystalline or polycrystalline materials that can produce diffraction peak of suitable intensity[3] [4] [5] [6].
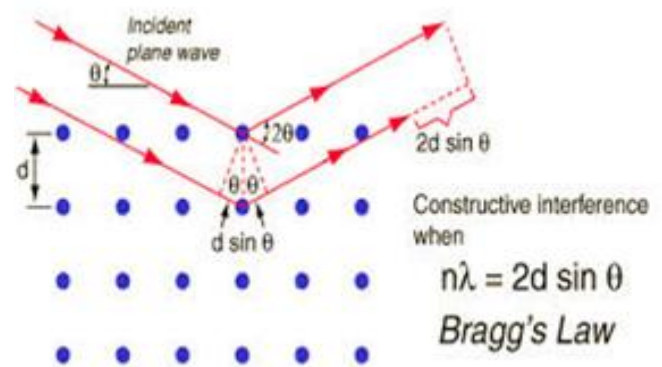

Fig2. Diffraction Phenomena and Bragg's Law [7].

Diffraction of electromagnetic radiation occurs when the X-ray radiation, which is

made to fall on the surface of the material comes in contact with atoms or crystallites of the material that are arranged in a regular array, for examples atoms in crystals (fig. 1). This radiation is absorbed and we get back them with the same frequency in terms of the strong and weak emissions on the different orientations. The angle at which the strong emission occurs is described by Bragg's Law [8]: $n\lambda = 2d\sin\Theta$. These redirected radiations are scanned. The angle at which we get the most intense radiation is established as the Bragg's Law.

The XRD techniques are capable of measuring the inter-atomic lattice spacing, which thus we get the amount of strain in the radiated part[9]. XRD is applied to work on the surface of the model. Electro polishing is a technique which is used to expose new surface for the deeper measurement [10].

2.1.1 Plane Stress Elastic Model [10]:
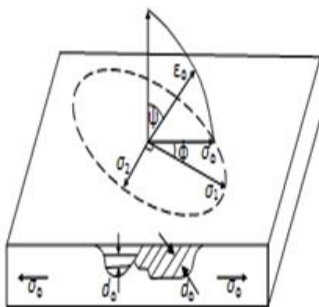
$$\text{sin}^2\psi \text{ method: } \sigma_\phi = \left(\frac{E}{1+v}\right)_{(hkl)} \frac{1}{d_{\phi 0}} \left(\frac{\partial d_{\psi}}{\partial \sin^2 \psi}\right)$$

Fig3. Plane stress at the free surface showing the change in lattice spacing with tilt ψ for a uniaxial stress σ_ϕ parallel to one edge,source [10].

X-ray penetration is a surface phenomenon, and so it is extremely shallow (<μm). A condition of plane-stress is assumed to exist in the diffracting surface layer. The stress distribution is described by principle stress σ_{11} and σ_{22} in the plane of the surface with no stress acting perpendicular to the free surface, as shown in the fig. 2. The normal component σ_{33} and the shear stress σ13=σ31and $\sigma_{12}=\sigma_{21}$acting out of the plane of the plane of the sample surface are zero. A strain component perpendicular to the surface ε_{33}exists as the result of the Poisson's Ratio caused by the two principle stresses.

The strain in the sample surface at an angle $\phi$from the principle stress σ11 is then given by [10]:

$$\varepsilon_{\phi\psi} = \left(\frac{1+v}{E}\right)\sigma_\phi \sin^2 \psi - \left(\frac{v}{E}\right)(\sigma_{11} + \sigma_{22})\text{(eq.1)}$$

The above equation relates the surface stress to the strain. This can be rewritten in terms of change in dimension:

$$\varepsilon_{\phi\psi} = \frac{\Delta d}{d_0} = \frac{(d_{\phi\psi} - d_0)}{d_0} \qquad \text{(eq.2)}$$

whered_0 is the stress free surface dimension.
Substituting eq.2 in eq.1, we get:

$$d_{\phi\psi} = \left[\left(\frac{v+1}{E}\right)_{hkl}\sigma_\phi d_0\right] \sin^2 \psi \left(\frac{v}{E}\right)_{(hkl)} d_0 (\sigma_{11} + \sigma_{22)}+d_0$$
(eq.3)

where the appropriate elastic constant $\frac{1+v}{E_{hkl}}$and$\frac{v}{E_{hkl}}$are now in the crystallographic direction normal to the lattice planes.

At $\sin^2 \psi = 0$, the intercept of the plot equals unstressed lattice distance, d_0 minus Poisson's Ratio contraction caused by the sum of the principle stresses.
Thus,

$$d_{\phi 0} = d_0 - \left(\frac{v}{E}\right)d_0(\sigma_{11} + \sigma_{22)},$$

Or,

$$d_{\phi 0} = d_0\left(1 - \left(\frac{v}{E}\right)d_0(\sigma_{11} + \sigma_{22)}\right)\text{(eq.4)}$$

The slope of the plot (fig4.) is given by,

$$\frac{\partial d_{\phi\psi}}{\partial \sin^2 \psi} = \left(\frac{1+v}{E}\right)\sigma_\phi d_0\text{(eq.5)}$$

which can be solved for the stress, σ_ϕ,

$$\sigma_\phi = \left(\frac{E}{1+v}\right)\frac{1}{d_0}\left(\frac{\partial d_{\phi\psi}}{\partial \sin^2 \psi}\right).$$
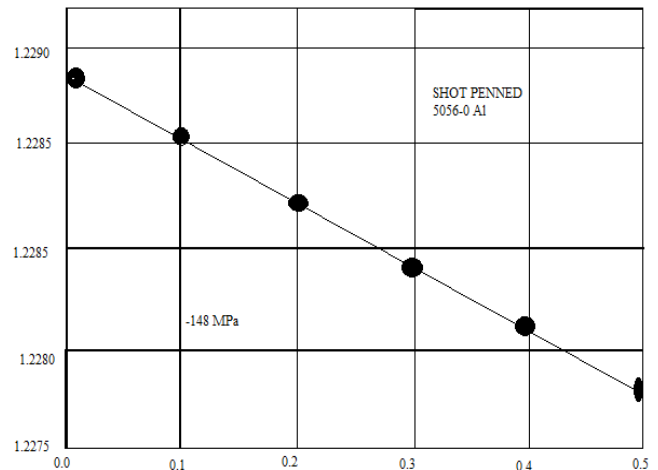

Fig4. Linear Dependence plot of d over $\sin^2 \psi$ for shot peened 5056 Al [6].

2.1.2 Stress Tensor Determination: an expression for the lattice spacing can be formulated as a function of $\phi$and ψ, for the general case, assuming stresses exist normalto the surface [11]. Nonlinearties producing separation of the +ψ and -ψ data in the form of elliptical curvature of the d-sin^2ψ plots termed "ψ splitting" are occasionally observed at the surface of ground hardened steels, and are attributable to shear stresses acting normal to the surface [12]. Determination of

the full stress tensor is necessary because of the deep penetration into the sample.

In principle, full stress tensor can be determined [11] [12]. However unlike the plane-stress model, the stress free lattice spacing, d_0 must be known independently to the accuracy acquired for strain measurement in order to calculate three stresses, $\sigma_{11}, \sigma_{22}, \sigma_{33}$.

2.1.3 Errors and Problems in XRD Technique:
There are few problems which are generally faced during the residual stress analysis by XRD technique [10] [13]. The errors can be broadly classified into three main points, sample dependents errors, analytical errors, and instrumental errors.

Sample dependents errors: Sample dependents errors can arise from an excessively coarse grain, severe texture, or interference of the sample geometry with the X-ray beam. Electro polishing for subsurface measurements will cause stress relaxation in the layers exposed. If the stresses in the layers removed are high and the rigidity of the sample is low, the relaxation can be the order of hundreds of MPa. Recently, some work is done in this direction to control it [14] [15].

Analytical errors: This error may arise from the validity of the stress model assumed, the use of inaccurate elastic constant, or the

method of diffraction peak location. Diffraction peaks several degrees wide must be precisely located. Various methods have been developed but the fitting of Pearosn 7 functions to separate the K suffix alpha doublet and allow for peak defocusing caused by the change in ψ angle and line broadening as layers are removed in the subsurface measurement is better [16] [17]. X-ray elastic constants may be determined empirically to ASTEM E1426 to accuracy on the order of $\pm 1\%$ in four point bending[18].

Instrumental errors: These arise from the misalingment of the diffraction apparatus or displacement of the specimen. Sample displacement from the centre of the goniometer is the primary instrumental error.

Also, XRD cannot be applied on large welds because of the limited space for the most beam lines [19].

B. Thermo ElasticStress Analysis Method:

It has been found that due to the residual strains, there is some change in the thermal energy of a stress induced material [20]. There is a relation of the rate of change of the temperature of a dynamically induced body is directly proportional to the principle stress, in ideal conditions, first found by *Lord Kelvin* [21] [22]. A method named SPATE (Stress Pattern Analysis by measurement of Thermal Analysis) is developed to detect changes in the infrared emission due to minute changes in the material of dynamically stressed material. However, recently it is found that the thermal response of a cyclically loaded body is also related to the static part [18] [19]. This finding led to the conclusion that this method can be used to the measurement of the residual stress.

The material experience a very small temperature **Δ**T [20], when the material is subjected to the cyclic loading that generates a cycle stress amplitude **Δ**σ under adiabatic conditions [23]:

$$\frac{\Delta T}{T} = -K\sigma$$

where K is the thermo elastic parameter.
Before the work of until Machin et al [24]

suggested that it is stress dependent. Then Wong et al. proposed [25] that K can be significantly dependent on the applied stress because of the thermal properties of the material.

The problem with this method is the occurrence of small changes in the thermal effect due to residual stress. So this method is confined and good for the comparative purposes.

C. Eigenstrain Reconstruction Method (ERM):

ERM is a method which is a combination experimental approach and application on the Eigenstrain theory. The experimental process is based on the diffraction process. This method has three essential part, the residual strain measurement, the solution of the inverse problem of the Eigenstrain Theory, and the simple triangle method.
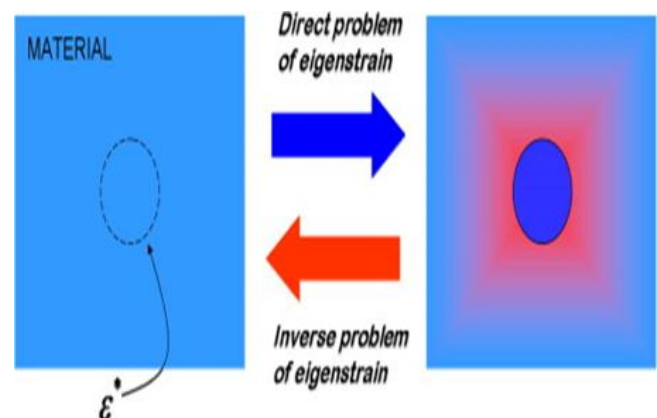

Fig5. Showing the Concept of Eigenstrain Reconstruction Method [26].

In this method, we can reconstruct the approximate residual stress and strain [26]. The term Eigenstrain was first coined by Mura (1982) [27]. This means any permanent strain in a material occurring due to some plastic load. It is denoted by ε*.

Thus the total strain in a deformed material is equal to,

$$\varepsilon_{total} = \varepsilon_\varepsilon + \varepsilon^*,$$

where ε_ε the elastic is strain and ε^* is theEigenstrain.

Then after the measurement of the strain, we apply inverse problem concept. Inverse problem is the step or process of finding the answer with the help of data available which is then based on the earlier experiments. There is also a direct problem method of Eigenstrain theory. In 1957, Eshelby[28], worked on the residual deformation due to uniform Eigenstrain within an ellipsoidal inclusion. His work for the Eigenstrain is considered as the ideal example for the direct problem concept.

III. CONCLUSION:

The methods studied in this paper are two non-destructive and one semi-empirical. The non-destructive methods are advantageous when it comes for the specimen preservation. The semi-empirical is vast and sophisticated way of stress determination. Each method studied above has its own advantages and limitations. XRD method is good when it comes to its application on the polycrystalline materials, ceramics, and fine over the larger weld and it is limited to the measurement of stress at the surface. Measurement using the thermoelastic method is based on simple science. And easy to be used. But again, it has its limitations. ERM is a semi empirical process. It is comparatively better that XRD because it rules out the limitations of it like lack of sensitivity for the permanent creep, as there is no change in the lattice arrangement. It is based on the experimental data and detailed analysis. But, it is a time taking sophisticated process and tough to be used in general. So, to measure the stress, the method should be chosen as per the exact situations, materials, time and money.

REFERENCES

[1]. Schajer*, G.S., Ruud**, C.O., "Overview of Residual Stress and Their Measurement"
*University of British Columbia, Canada
**Pennsylvania State University, USA

[2].Molzen*, M.S., Hornbach**, D.J., "Evaluation of Welding Residual Stress Levels through Shot Penning and Heat Treating", *MetalImprovement Company, Co. Inc., **Lambda Research Inc. 2000-01-2564, Copyright 2000 SAE, Inc.

[3]. M.E. Hilley, Ed., Residual Stress Measurement by X-ray Diffraction, SAE J784a, Society of Automotive Engineers, Warrendale, P.A., p 21-24.

[4]. Cullity, B.D., Elements of X-ray Diffraction, 2nd ed., p 447-76, Addison Wesley, Reading, Massachusetts (1978).

[5]. Noyan, I.C. and J.B. Cohen, "Residual Stress Measurement by Diffraction and Interpretation", Springer-Verlay, New York (1987).

[6]. P.S. Prevey, "Metals Handbook Ninth Edition", Vol.10, K. Mills, pp380-392, Am. Soc. for Met., Metals Park, Ohio (1986).

[7]. Nave, C.R., Bragg's Law, Hyperphysics, Georgia State University.

[8]. Bragg, W.L. (1913). "The Diffraction of Short Electromagnetic Waves by a Crystal". Proceedings of the Cambridge Philosophical Society, 17: 43:57.

[9]. SAE (2003) Residual Stress Measurement by X-ray Diffraction, SAE J784, Society of Automotive Engineers Handbook Supplement, Warrendale, PA.

[10]. Prevey, P.S., X-ray Diffraction Residual Stress Techniques, Lambda Research.

[11]. Dolle, H. and Cohen, J.B., MetTrans, 2ndA (1980).

[12]. Dolle, H., J. Appl. Cryst, 12.498 (1979).

[13]. Lasse Suominen, D.Carr, Copyright JCPDS, International Centre for Diffraction Data 2000, Advances in X-ray Analysis, Vol.43.

[14]. Moore, M.G. and Evans, W.P., Trans SAE, 66, 340 (1948).

[15]. Hornbach, D.J., Prevey, P.S., and Mason, P.W., "X-ray Diffraction Characterization of the Residual Stress and Hardness Distribution in Induction Hardness Gear", Proceedings First International Conference on Induction Hardened Gears and Critical Components, Gears Research Institute, (1995), pp 69-76.

[16]. Prevey, P.S., Adv. X-ray Anal, 29, 103-111 (1986).

[17]. Gupta, S.K. and Cullity, B.D., Adv. X-ray Anal, 23,333 (1980).

[18]. Prevey, P.S. Adv. X-ray Anal, 20, 345 (1997).

[19]. Rossini, N.S., Passiti, M., Benyounis, K.Y., Olabi, A.G., "Methods of Measuring Residual Stress in Components".

[20]. Du, Y., Backman, D., Patterson, E., "A New Approach Measuring Surface Residual Stress using Thermoelasticity, June 2-5, Copyright, Society of Experimental Mechanics Inc. (2008).

[21]. Wong, A.K., Dunn, S.A., Sparrow, J.G., Nature 332, 613-615 (14 April, 1988.

[22]. Thompson, W. (Lord Kelvin) Trans. R. Soc. Edinb. 20, 261-288 (1853).

[23]. Hardwood, N., Cummings, W.M., "Thermoelastic Stress Analysis, Adam Hilger Publs, Bristol, UK (1991).

[24]. Machin, A.S., Sparrow, J.G., Stimson, M.G., "Mean Stress Dependence of the Thermoelastic Constant", Strain, 23 (1987), 27-30.

[25]. Wong, A.K., Jones, R., Sparrow, J.G., "Thermoelastic Constant or the Thermoelastic Parameter?" J. Phys. Chem. Solids, 48 (8): 749-753, (1987).

[26]. Jun, T-S, Korsunsky, A.M., "Evaluation of Residual Stress and Strains Using the Eigenstrain Reconstruction Method", International Journals of Solids and Structure, Vol.47, Issue 13, 15 June 2010, Page 1678-1686.

[27]. Mura, T, "Micromechanics of Defects in Solids, The Hague, London, Martinus, Nijhoff (1982)

[28]. Eshelby, J.D., " The Determiniation of the Elastic Field of an Ellipsoidal Inclusion, Proc Roy Soc Lond, 241:376-396, (1957).