RESIDUAL STRESS PRODUCED AFTER MACHINING IN MECHANICAL COMPONENTS AND ITS EFFECTS ON FATIGUE LIFE: A STATE OF ART

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ABSTRACT

The residual stresses are produced during metal working of engineering components before they are exposed to the service. This phenomenon is dominant in machining processes where cutting tool and work material are in contact with each other and as a result of elastic-plastic deformation of the material, heat treatment. Such stresses are found to have a very significant effect on the fatigue life of components. Those stresses that exist in a machine part without external loading being present, these residual stresses are “locked into” the component in the absence of external loading and represent a datum stress over which the service load stresses are subsequently superimposed. An exhaustive research is necessary to measure and control such stresses so that corrective measures can be taken while designing the components for expected service. This paper presents an exhaustive literature on the development of residual stresses in machining processes in general and turning operation in particular.

KEYWORDS: Residual Stresses, Fatigue Life, Surface Integrity, Fatigue Performance, Fatigue Crack Growth, Etc

INTRODUCTION

The residual stresses play an important role in fatigue life of engineering components. All engineering components before being subjected to service loading conditions contain stresses owing to the history of the material prior to such service. The stresses produced during elastic-plastic deformation in mechanical working of the material, heat treatment, chemical treatment, joining procedure etc., are termed residual stresses [1]. These stresses may vary in depth, magnitude and sign. Such stresses are usually produced while manufacturing parts and can have a very significant effect on the fatigue life of components [2].

Residual stress can be tensile or compressive and the stressed layer can have multiple depths, depending upon the cutting conditions, work material, cutting tool geometry and contact conditions at the tool/chip and tool/work piece interfaces [3]. As shown in figure 1, the compressive residual stress close to the surface of the work piece is high and decreases as the depth increases. At certain depth the residual stress becomes negligible and further increase in the depth results into tensile residual stress. Compressive residual stresses generally improve component performance and life because they promote service stresses and prevent crack nucleation. On the other hand, tensile residual stresses tend to increase service stresses which lead to premature failure of components [3].
The literature on the effect of residual stresses on the performance of components is available under different keywords like residual stress, machining parameters, surface integrity, fatigue life, fatigue, machining, manufacturing processes, fatigue performance, fatigue crack growth, etc. The literature available on different machining processes is collated together and presented in six different sections.

- Development of residual stresses
- Mathematical and simulation models
- Experimentation carried out
- Measurement techniques
- Other machining processes

DEVELOPMENT OF RESIDUAL STRESSES

Residual stresses generally arise when conditions in the outer layer of a material differ from those internally. The most significant mechanical processes which induce surface residual stresses are those which involve plastic yielding. Practically all standard machining processes such as grinding, turning, polishing etc. involve local yielding and hence induce residual stresses [4]. It has been observed that plastic deformation is almost invariably present in any machining process. The extent of the plastically deformed layer, and hence the residually stressed region will depend on the depth of cut, sharpness of tool, rates of speed and feed, and the machinability of the material.

Two distinct kinds of residual stresses i. e. macrostresses and microstresses exist with an inherent difference between them. Macrostresses are those residual stresses which are in equilibrium within macrodomains, covering volumes comparable in size to the part; they concur with the concept of isotropic material. Microstresses are crystal within single metal grain or group of grains in equilibrium within volumes comparable with dimensions of the grains. These include submicroscopic stresses which relate to distortion in atomic lattices of crystals [1].

Macostresses have been widely investigated, including the reasons for their occurrences and how they affect the strength and other properties of metal. Normally the macrostresses are listed in technical specifications of parts and are inspected in surface layers after manufacturing [2]. Macrostresses, in general, are either tension stresses or compressive stresses. Residual tension stresses are detrimental, since they reduce fatigue strength and impair wear and corrosion resistance of machine parts. Compression stresses, to the contrary, are believed to be beneficial. In the manufacture of
machine parts the residual stresses are grouped accordingly to the shape and trajectory of the processing tool: tangential, in the displacement; and radial, perpendicular to the processed surface [1]. The creation of residual stresses is caused by elastic-plastic deformation, which takes place in the contact area between the tool and workpiece and is sometimes by high temperatures.

There are number of factors attributed to the origin of residual stresses. Under the action of the tool on the processed metal surface in machining process, three domains are formed in the surface layer: plastically deformed metal, elastically deformed metal, and unaltered initial state [1]. The plastically deformed metal has lower density and therefore higher specific volume. The internal layer prevents the increase of volume of plastically deformed metal resulting in residual compression stress in the outer layer and tension stresses in inner layers [1]. As tool moves along the processed surface, it stretches crystalline grains of surface layer, subjects to elastic and plastic tension deformation. This process is aided by friction of the tool on the processed surface. After the tool leaves the surface, the plastically stretched layer, bonded to inner layers, acquires compression stresses. Accordingly, the inner layers develop residual tension stresses for counterbalancing. The heat released in the processing area instantly heats a thin surface layer to a high temperature, increasing the specific volume. On termination on tool action a rapid cooling of the surface layer takes place causing a compression. The high pressure and temperature during deformation cause structural phase transformation in the surface layer. This is accompanied by a change in volume. When the specific volume of surface layer increases, residual compression stresses develop. When the specific volume decreases, residual tension stresses appear. These residual stresses may affect dramatically the performance of the machined part causing its premature failure or excessive wear.

**MATHEMATICAL AND SIMULATION MODELS**

The mathematical models for measurement of fatigue life and determination of residual stress beneath suggested by different investigators are presented in table 1.

Difference authors studied effects of residual stresses on fatigue life of components either through mathematical model or simulation models. The purpose of developing these models has been different. They are either to measure the constant, or predict characteristics of residual stresses, or to evolve relation between turning parameters and residual stresses, or to measure penetration forces.

**Table 1: Mathematical and Simulation**

<table>
<thead>
<tr>
<th>Author</th>
<th>Mathematical and Simulation Model</th>
<th>Findings &amp;Remarks</th>
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<tbody>
<tr>
<td>T.D.Marusich and E. Askari [4]</td>
<td>Simulation model for turning, Metal cutting operation for thermo-mechanical properties, cutter geometry and process parameters.</td>
<td>Studied machining simulation software AdvantEdge, which integrates advanced finite element numeric and material modeling appropriate for machining to indicate the magnitude and sign of the state of stress.</td>
</tr>
<tr>
<td>Meng Liu et.al. [9]</td>
<td>$\sigma_{\text{max}} = r_1 - \sqrt{r_1 \sin \left[ \cos^{-1} \left( \frac{H-2}{H} \right) \right] - \Omega^2 + (H-a)^2}$</td>
<td>To determine the residual stress beneath the machined surface, an electro-polishing technique is utilized, and the electro-polished depth from machined surface is over 200 $\mu$m. The value of constant is measured.</td>
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<td></td>
<td>$I_z = r_1 \left[ \cos^{-1} \left( \frac{H-2}{H} \right) + \sin^{-1} \left( \frac{f}{2r_1} \right) \right]$</td>
<td></td>
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<tr>
<td></td>
<td>$k_{\text{ref}} = \tan^{-1} \left[ \sqrt{\frac{H-2}{H}-\frac{H-a}{H}} \right]$</td>
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<td></td>
<td>Where, $k_{\text{ref}}$ is reference cutting edge angle, $F_i$ is cutting force, $F_f$ is feed force, $F_T$ is thrust</td>
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<tr>
<th>Author(s)</th>
<th>Description</th>
<th>Mathematical Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y.B. Guo and David W. Yen</td>
<td>Simulation model using finite element analysis for residual stresses considered roller radius, number of passes for turning and grinding.</td>
<td>Prepared simulation model using finite element analysis for residual stress by considering roller radius, number of passes, distance per pass, rotation speed, friction speed, friction coefficient and displacement etc. This simulation applies to both elastic and plastic deformations in rolling contact.</td>
</tr>
<tr>
<td>Edoardo Capello</td>
<td>$\sigma_z = 1000 \log \left( k_f r^\gamma \right) - k_4 \chi$</td>
<td>Present mathematical model for fatigue life through the rolling contact fatigue test. The results showed that the predicted accuracy of this model can be enhanced significantly by incorporating residual stresses and its influence on the rolling contact fatigue life by more than 40%.</td>
</tr>
<tr>
<td>G.F. Batalha et al. [18]</td>
<td>$F_p = 6.96 + 317.35 f + 375.73 p + 2515.42 f p$</td>
<td>Studied experimental model for force and stresses &amp; measured values of the penetration forces.</td>
</tr>
<tr>
<td>Youngsik Choi [27]</td>
<td>$N = \frac{1}{\sigma_{max} - \sigma_{min}} \int_{\sigma_{min}}^{\sigma_{max}} \left( f d \sigma + \Delta \sigma k_f \right) d \sigma$</td>
<td>Presented mathematical model supported by simulation and experimentation, for residual stress profiles in cutting/tangential direction to predict characteristics of residual stress profile. The predicted characteristics of residual stress profile favorably agree with the measured ones.</td>
</tr>
<tr>
<td>Y.B. Guo [31]</td>
<td>$\phi = b - w^\gamma \sigma + w^\delta = \lambda \mu (D^\gamma) + 2 \mu D^\delta$</td>
<td>Studied simulation in machining tool advances in the workpiece in cutting direction to form the chip, it exerts tremendous pressure on work material in cutting direction as well as a significant amount of thrust in the downward direction. It is a thermal-mechanical based hybrid FEA modeling.</td>
</tr>
<tr>
<td>S. Anurag et al. [34]</td>
<td>Simulation model for turning and grinding.</td>
<td>Prepared simulation model on case study for residual stresses in machining of SS AISI 316 using FEM analysis. Cutting parameters such as a feed rate as well as rake angle are simulated to evaluate residual stresses. Residual stress mechanism is found to be influenced by process parameters.</td>
</tr>
<tr>
<td>C. Maranhao and J.P. Davim [41]</td>
<td>Simulation model using finite element analysis for residual stresses considered during machining materials with special emphasis steel.</td>
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</table>

Therefore, the relationship between residual stresses and fatigue life cannot be clearly established. Even though the preliminary mechanism of development of residual stresses is available, the literature does not indicate the cause for its effect on fatigue life mathematically.

**EXPERIMENTATION**

Table 2 presents experimentation carried out by various investigators indicating experimentation process adopted.
work materials used, machining parameters considered and the findings.

Table 2: Experimentation

<table>
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<tr>
<th>Author</th>
<th>Experimentation and Findings</th>
<th>Remark</th>
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<tbody>
<tr>
<td>El-Axir[7]</td>
<td>*1-Turning, *2-Stainless Steel-304, Steel-37, 7001, 2024-Aluminum Alloy, and brass. *3-Tensile strength, cutting speed and feed *4-Residual stress continued to decrease across the section; become either tensile or compressive at large depths. Cutting speed $x_1 = 2(\log V/\log V_t) / \log V_t - \log V$, Feed rate $x_2 = 2(\log F/\log F_t) / \log F_t - \log F$, Tensile strength $x_3 = 2(\log T/\log T_t) / \log T_t - \log T$, Surface $e = 18.425 + 0.769v + 5014f + 26.2m + 3.125vf + 24.3vm + 13.125fm$ Where $V$, $F$ and $T$ are cutting speed, feed and tensile strength of the material, respectively.</td>
<td>The parameters like depth of cut, tool geometry, tool material and cutting oil not studied. Present comprehensive experimental model which has the capability of predicting residual stress profile.</td>
</tr>
<tr>
<td>Edoaedo [14]</td>
<td>*1-Turning, *2-Fe370 C45,39 Ni Cr Mo3 Steel, *3-side relief angle, rake angle, cutting velocity, *4-surface residual stresses in axial direction can be tensile or compressive depending on process parameters and on the characteristics of the machined material. A material with higher mechanical properties will present larger residual stresses.</td>
<td>tensile or compressive stresses depending on process parameters</td>
</tr>
<tr>
<td>Edoaedo [15]</td>
<td>*1-Turning, *2-carbon and alloy steel, *3-feed rate, nose radius, *4-The increment in residual stresses due to an increment in process parameters does not seem to be influenced by the machined material.</td>
<td>parameters does not influence by the machined material.</td>
</tr>
<tr>
<td>Meng Liu[9]</td>
<td>*1-Turning. *2-Bearing steel JIS-SUJ2, *3-Nose radius, depth of cut *4-The effects of the nose radius on the residual stress distribution decreases greatly with the increase of the tool wear.</td>
<td>Measured cutting forces, to determine the residual stresses beneath the machined surface. Electro-polishing technique is utilized for acquiring required depth.</td>
</tr>
<tr>
<td>Hiroyuki [12]</td>
<td>*1-Turning, *2-0.45% C steel, *3-Nose radius of the tool and feed rate were varied and two kinds of tool edges. *4-Higher fatigue life to the machined components comparing with the virgin material if compressive residual stress and high hardness within surface layer can be induced by cutting process.</td>
<td>Cutting speed, cutting force, coolants are not studied.</td>
</tr>
<tr>
<td>Ataollah Javidi [21]</td>
<td>*1-Hard Turning, *2- Steel 34CrNiM06, *3- Cutting Speed, Feed, Nose radius, *4-higher compressive residual stress causes a higher fatigue life and the effect of residual stress on fatigue life is more than the effect of surface roughness.</td>
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<tr>
<td>Outeiro [25]</td>
<td>*1-Turning, *2-Inconel 718, Austenitic stainless steel AISI 316L with coated and uncoated tools. *4- Higher surface residual stresses are generated when machining with the uncoated tool than the coated tool.</td>
<td>-----</td>
</tr>
<tr>
<td>Guo and Warren[26]</td>
<td>*1-Hard Turning and Grinding, *2-Stel AISI 52100, *3-Cutting velocity, feed, depth of cut for turning and grinding, wheel speed, table speed, cross feed, down feed, coolant. *4- Magnitude of residual stress generated by hard turning is more than 3 times larger than grinding and depth is nearly 2 times deep.</td>
<td>Studied the hook shaped Residual stress profile of a turned surface.</td>
</tr>
<tr>
<td>Youngsik Choi [27]</td>
<td>*1-Turning, *2-Steel AISI 1053, *3-Cutting speed, Nose radius, feed, depth of cut, and coolant type. *4- Residual stress could increase the rolling contact fatigue life by around 12 times.</td>
<td>Not considered machining parameters.</td>
</tr>
</tbody>
</table>
There is no uniformity in conducting experimentation as regards to the type of machining processes and the variables selected. Though many machining parameters like cutting speed, feed, depth of cut, tool nose radius, coolant type, cutting force etc. are found to influence the fatigue life, they have been studied in isolation. Therefore, no clear relationship can be established between cutting parameter responsible for developing residual stresses and further its effects on fatigue life. Hence the disparity in the findings are not unnatural. It can further be observed that no much experimental models are available in literature to establish relationship for influence of cutting parameters on residual stresses.

**MEASUREMENT TECHNIQUES**

The literature indicates that the residual stresses are measured using either by non-destructive testing or by destructive method. X-Ray diffraction techniques are used for non-destructive testing. However, the output is measured in different from which is then converted in residual stress.

Thomas R. Watkins et al. [3] on the basis of sin²θ plot suggested the possibility of the presence of both residual stress and composition gradients as a function of depth, given the nature of the steel nitriding process. The amount of nitrogen as a function of depth is determined using an electron microprobe. Laplace transform function is used to convert...
the microprobe data to an exponentially weighted volume average as sampled with X-ray diffraction. A. T. Fry and J. D. Lord [32] the proposed measurement of residual stresses by X-ray Diffraction to examine various aspects of the XRD test procedure. Danial Magda, [24] studied two methods for measuring residual stresses. First is the mechanical relaxation dissection method (destructive testing) which is very time consuming and inherently destructive. This method utilizes strain gauges to measure the strain relaxation after the part is sectioned away from the main body. Second method depends that is the techniques of residual stress measurement by X-ray diffraction. Where spacing of the atomic (hkl) planes in a metal material is altered by stress which can be determined by measuring the angular position of a position of a diffracted X-ray beam. G. A. Webster and A. N. Ezeilo, [5] studied the neutron diffraction non-destructive technique has been described. P. J. Withers and H. K. D. H. Bhadeshia, [6] studied that, residual stresses are difficult to predict than the in-service stresses on which they superimpose.

It can be seen that X-ray diffraction technique is more suitable and it has advantage over mechanical methods owing to the destructive part. Further microstresses cannot be measured by mechanical methods.

RESISUAL STRESS IN OTHER PROCESSES

The literature also available for measurement of residual stresses and its effect on fatigue for other machining processes. M. Suraratchai [22] et.al. and Zhongyi et.al.[37] have studied milling process. A. Kortabarriaet.al. [38] has studied for drilling process. The study on grinding process has been presented by Masayuki et.al. [36] and Yuuji Shimatani et al. [35] and B. A. Show et.al. [8]. Rahman Seifi [23], G. Pouget and A. P. Reynolds [20] and M. N. James et. al. [19] have studied welding process. Diana A. Lados et. al.[17] studied the casting process. G. A. Webster and A. N. Ezeilo [5] studied forging process. J.J.Williamset.al.[16] studied in cold pressing and sintering process. Dongtao Jiang et.al,[13] studied EDM process.

CONCLUSIONS

The literature reveals that:

Though residual stresses play significant role in fatigue life of mechanical components, the study so far dose not establish the causes and processes how to control the development of fatigue life.

It also seen that compressive residual stresses are conducive while tensile residual stresses affect the fatigue life adversely further it different investigators have considered different parameters while performing experimentation.

The certainty of type of residual stresses beneath the machined surfaces and the corresponding depth is not yet known. It can be said that the type of residual stresses on the machined surfaces and beneath depends on the machining parameters used. However, it is not yet established mathematically or experimentally.

As the mathematical models do not reveal the machining parameters so as to estimate the type and amount of residual stresses developed on machining the component, they are having useful for practical processes.

Therefore, a fresh attempt is necessary to establish the relationship between cutting parameters in machining processes and the corresponding residual stresses developed. Such attempts are expected to help in improving fatigue life of machined components.
REFERENCES


28. Tadeusz Leppert, [2009] c “Surface Residual Stresses in Dry Turning of 0.45% C Steel”, International Centre for Diffraction Data, ISSN 1097-0002.


