



# A Review on Measurement Methods for Machining Induced Residual Stress

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## ABSTRACT

The chip formation in mechanical machining / cutting process involves thermal loading and mechanical loading in the form of large plastic deformations, high strain, strain rates and high temperatures in the cutting zone. These loadings usually induce plastic deformation in the form of residual stresses in the surface and sub-surface of the machined workpiece. Residual stress issue is essential to be studied in order to control the quality and fatigue life of a component or part produced by machining process. Therefore, the magnitude and depth of the residual stresses into the workpiece sub-surface is important and necessary to be measured. The objective of this paper is to discuss various study on the effects of machining parameters on residual stress and residual stress measurement methods for machined workpiece namely non-destructive, semi-destructive and destructive methods. In addition, the effect of machining process into the metal-lurgical conditions of the workpiece in the form of microstructural changes is also discussed.

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## 1. INTRODUCTION

Cutting or machining is a mechanical material removal process in which the cutting action is performed by a tool with higher hardness than the workpiece material. In the simplest form of cutting, viz. orthogonal cutting (**Figure 1**), the cutting

edge is perpendicular to the cutting velocity ( $v_c$ ) and as the tool moves towards the workpiece with constant depth of cut ( $t_0$ ), the chip forms and separates from the workpiece near the cutting edge and generates a plane surface. The chip formation is accompanied with large plastic deformations, high strain (1 – 4), strain rates.

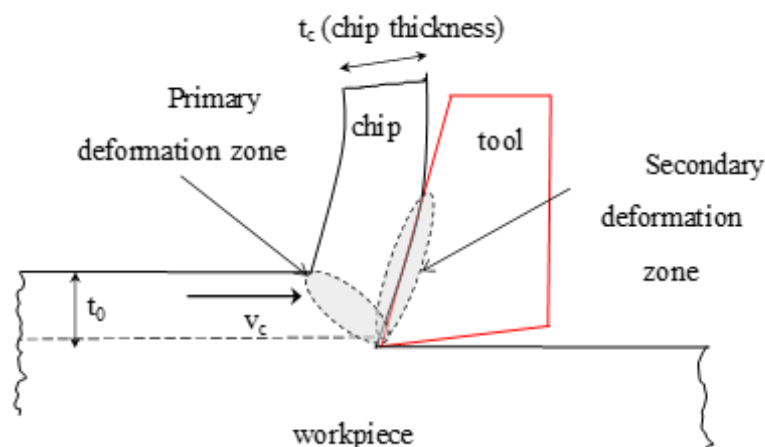


Figure 1. Schematic view of orthogonal cutting.

( $10^4 - 10^6 \text{ s}^{-1}$ ), and high temperatures in the cutting zone ( $700 - 1000^\circ\text{C}$ ). The deformation in the process can be regarded as occurring in a plane strain where the chip does not flow to either side and the width of the tool is greater than that of the workpiece (Shaw, 1984).

The machining process involves thermal loading and mechanical loading, which can generate surface and sub-surface damage or deformation altering mechanical and metallurgical properties of the machined workpiece and furthermore induce residual stresses (Treuting and Read Jr., 1951). The deformation occurred in the form of residual stresses can be measured quantitatively and qualitatively using different methods. Residual stresses can be used to evaluate the machining process because residual stresses are a sensitive indicator for variations of machining parameters and tool properties (Brinksmeier and Tönshoff, 1985).

In general, materials affected by plastic deformation have force states, irregular shape (Nurprasetio *et al.*, 2017), and inhomogeneous properties, resulting in the alteration of materials unevenly after the process and subsequently residual

stress will be generated. In the microscopic point of view, residual stress can be considered as the permanent change in the plastic region (for the case of elastic-plastic materials) of the microstructures in the form of stretching and distortion after the load is removed (Ruud, 1986). The residual stress not only arises in plastic deformations process but also other mechanisms such as temperature variation and structural transformation (Yuan *et al.*, 2018). The higher residual stress produced in machined part will shorten the life cycle of the part. Therefore, it is important to control the existence of residual stress to avoid any failures in a product.

The intention of this paper is to discuss and review some efforts from researchers in identifying the effect of machining parameters on residual stress and measuring residual stress on machined workpiece. This discussion will be emphasized on various residual stress measurement methods proposed and utilized by researchers reported in the literature. The first part of this paper discusses about machining induced stress, followed by discussion on various quantitative residual stress measurement methods. The quali-

tative measurement method by observing microstructural changes is also explored. It is expected that the residual stress measurement methods discussed in this paper can be articulated and used as a guidance by researchers and industries involved in machining works.

## 2. MACHINING INDUCED RESIDUAL STRESS

This section discusses some research results on the identifying residual stress induced in machining and the effect of machining parameters on residual stress. Many experimental findings, analytical modelling, finite element, neural networks and various combination of these methods have been conducted in studying the residual stress (Hanna, 2007). Residual stress in the machining process can be defined as the distribution of stresses on and beneath the machined surface of the workpiece after it has achieved its equilibrium state and all fixturing have been released and the workpiece cools down to a room temperature (Fang and Zeng, 2005). Besides relieving the residual stress, new stresses are also induced by the tool on the surface of the workpiece which influence the original residual stress distribution (Rathbun and Coffin, 1966). Jacobus et al. (Jacobus et al., 2000) proposed a de-

tailed analysis of the phenomena that occur in machining (**Figure 2**):

Case 1: when the thermal strain is less than plastic deformation causing compressive residual stress in the surface and sub-surface.

Case 2: when the thermal strain is more than plastic deformation causing the surface and near the surface to become tensile and the sub-surface compressive.

Case 3: when the plastic deformation in the sub-surface is less than zero causing the stress in the surface and sub-surface to become tensile.

Residual stress is also used to describe the amount of thermal or mechanical influence on the workpiece deformation (Ramesh *et al.*, 2004). At high cutting speed, the thermal load will be more dominant and causing tensile residual stresses in the machined surface, whereas the mechanical load will have greater effect in low cutting speed and furthermore induces compressive residual stress (Sharman *et al.*, 2006). Tensile residual stress is detrimental for the machined workpiece because it can generate fatigue and stress corrosion cracking (von Turkovich and Field, 1981). Compressive residual stress, in contrast, is favorable to avoid such problems.

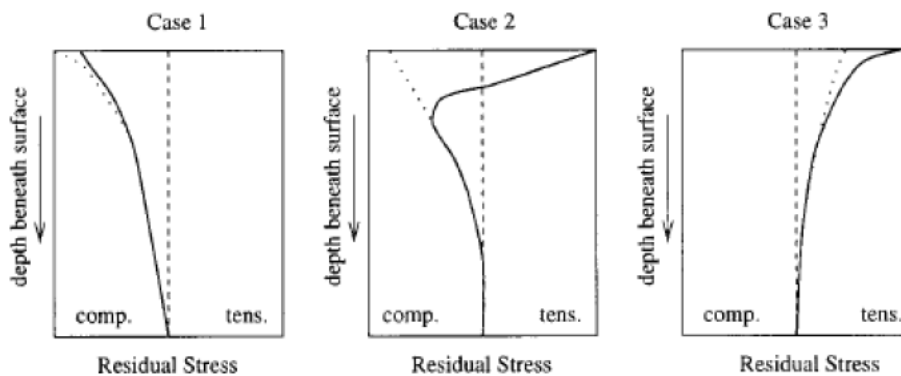


Figure 2. Possible residual stress profile resulting from the machining process (Jacobus *et al.*, 2000).

Not only the nature of residual stress important, but also its magnitude and depth into the workpiece sub-surface is of importance. The residual stresses profile caused by manufacturing processes usually shows very steep profile to depth gradients (Ruud, 1986). Residual stress as deep as 200  $\mu\text{m}$  was observed when cutting AISI 4340 with the depth of cut 200  $\mu\text{m}$  (Jacobus *et al.*, 2000). Guo *et al.* (Guo *et al.*, 2006) observed the residual stress is tensile at a depth of 20  $\mu\text{m}$  and changes to be compressive at 100  $\mu\text{m}$  in the high speed milling of aluminium alloys. In addition, the depth of residual stress is dominantly affected by the mechanical loading (Tang *et al.*, 2009).

The machining induced residual stress influences the internal stress equilibrium state and in the end re-distribute the in-plane and out-of-plane stresses (Robinson *et al.*, 2011). The distribution of out-of-plane stress contributes significantly to the final state of the workpiece. Out-of-plane residual stresses (through the cross section) of component is usually most relevant in the case of distortion of the component rather than the location or magnitude of the maximum tensile residual stress (Ruud, 1986) and may lead to fracture. The in-plane residual stresses are not visually detectable but can promote slow crack growth as in the stress-corrosion cracking of metals, or fast fracture as in the brittle fracture of ceramics and glasses (Andonian and Danyluk, 1985).

The study of residual stress formation in machining process focuses on the cutting conditions as one of the dominant factors that could detriment to part quality. Masmiasi and Sarhan (Masmiasi and Sarhan, 2015) identified the ideal cutting

parameters and better surface integrity in inclined end milling through microhardness and residual stress analysis. Microhardness and residual stress are greatly affected due to the variation of the inclination angle. It was observed that the axial depth of cut is indirectly proportional to the microhardness and axial depth of cut is the dominant cutting parameters affected the microhardness. As the axial depth of cut became lower and the cutting path became higher, thermal effect induced on the machined surface is increased as well as rapid workpiece heating is occurred, resulting in higher hardness on the surface (Triawan *et al.*, 2018).

Huang *et al.* (Huang *et al.*, 2013) examined the relation of milling-induced residual stresses in feed and cutting direction with the process parameters in the machining of aluminium alloy 7050-T7451. The results showed that lower cutting speed produced less heat accumulation in the chips, thus the heat dissipates into the machined surface was high, resulted in less formation of residual stress. Moreover, lower feed rate produced a lower cutting force, resulting less compressive residual stress. The cutting temperature varies with the changes of depth of cut, resulting in fluctuation of compressive residual stress variation. Thus, the increment cutting speed shows a greater impact on the formation of compressive residual stress, followed by feed rate and depth of cut. While the increment of width of cut shows no significant effect. A compressive residual stress layer was reportedly generated at higher cutting speeds due to the effect of the higher machining forces in the face milling of 7075-T7451 aluminium alloy (Perez *et al.*, 2018). In contrast, tensile residual stress was generated at lower cutting speeds.

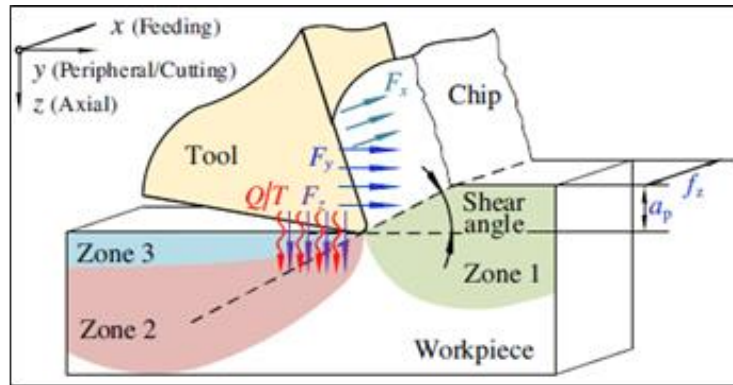


Figure 3. Simplified analytical model of the cutting loads and stress zones (Ma *et al.*, 2014)

Ma *et al.* (Ma *et al.*, 2016) studied the relation between surface residual stress and thermo-mechanical loads. They argued that cutting forces and temperature were unreliable to predict the formation of residual stress of machined surface. Thus, the three stress zones near the cutting area was the concerned (**Figure 3**).

The experimental results showed that at given cutting condition, tensile residual stress was generated along the peripheral direction,  $\sigma_{yy}$  at the central point of the machined surface due to the thermal effect in end milling. In addition, the presence of compressive residual stress was observed along the peripheral direction due to mechanical effect influenced by the cutting forces. By comparing both formations, the thermal effect has a major influence under the selected cutting conditions. The addition of coolant during milling decreases cutting temperature, improves surface quality and generates compressive stress. Wang *et al.* (Wang *et al.*, 2017) argued the residual stresses layer is about 80  $\mu\text{m}$  below the machined surface. The tensile residual stresses magnitude increases with the increased of lead / spindle angles in the ball end milling of Inconel 718. In the turning of Inconel 718, the cryogenic method also produced

larger compressive stresses about 100 MPa than dry machining with the depth of compressive residual stresses extent down to 250  $\mu\text{m}$  in the sub-surface (He *et al.*, 2016).

Simulation has also been used to study residual stresses effect in the machining. The metal cutting simulation using finite element method showed the increase in the tool-chip interfacial friction coefficient resulted the residual stress shifted from tensile to compressive (Shet and Deng, 2003). The FE analysis of residual stress performed by Ulutan *et al.* (Ulutan *et al.*, 2007) showed the results are very close to the residual stress measured using X-Ray Diffraction (XRD) method. A prediction model for residual stress using an Artificial Neural Networks with Radial Basis Function model was developed for ball nose end milling process of AISI H13 steel (Reimer and Luo, 2018). The model is based on cutting parameters such as cutting speed, feed rate, depth of cut and tool lead angle. The results from the model were compared with those measured using XRD method. The residual stress prediction results produced more consistent and precise prediction.

Residual stresses can be reduced or completely relaxed by the application of

mechanical and/or thermal energy. Relaxation of residual stresses occurs by the complex interaction of a large number of factors. It depends not only on the residual stress state itself but also on the material state, loading condition, geometry and environment of the component under consideration. One of the simple and well-known residual stress relaxation methods is the annealing process (Walton, 2002).

### 3. RESIDUAL STRESS AND DEFORMATION MEASUREMENT METHODS

This section discusses some measurement methods proposed and used by researchers in order to quantify the residual stress induced in machining. Residual stress effect especially due to the machining process is significant to be measured in order to analyze and predict the life of a component. The residual stress basically is determined indirectly by measuring the elastic strain. There are various methods have been introduced to measure the effect of residual stress in a machined workpiece over the years. Residual stress measurement methods can be categorized into destructive, semi-destructive and non-destructive technique as shown in **Figure 4**. The different method has a different advantages and limitations. It is important to obtain a reliable assessment from the method that being used. Each of the method will be explained in the following paragraphs.

Destructive method relies fundamentally on stress-relaxation procedure obtained by relaxing the residual stress in some finite-volume element of the component, normally by removing some stressed material, and measuring the resulting strain change (Ruud, 1986) thus the specimen may no longer be able to re-

turn to the service (Shokrieh and Ghanei Mohammadi, 2014). The material removal or cutting process changes the geometry and boundary conditions of the specimen material, and thus changes material elastic response to the (unchanged) inherent strains. Destructive method is suitable for measuring the residual stress profile.

Sectioning technique and contour method are some examples of the destructive method as shown in **Figure 5**.

Contour method is one of the preferable destructive technique used to measure the residual stress effect (Kartal, 2013). Typically, this method carries out by cutting the interest selected area to be deformed due to residual stress relaxation of the experimental sample. Then, finite element model is conducted to examine the out-of-plane residual stress distribution at the cut surface (Dive et al., 2017).

However, a study by Kartal (Kartal, 2013) has successfully removed the need of finite element analysis and provided an analytical solution for semi-infinite strip and finite rectangle in order to calculate the measurement data of residual stress. In addition, the non-destructive method such as XRD can also measure the residual stress profile by coupling with the layer removal process, which makes the method destructive. However, the cutting or removal layer of materials must not introduce new stresses induced by the process which can disturb the original residual stress in the specimen. The electrolytic polishing method is a suitable removal layer process for such measurement (Ruud, 1986). Any areas affected by the surface roughness generated by polishing should be avoided as it may disturb the diffraction pattern when using XRD.

## RESIDUAL STRESS MEASUREMENT METHODS

Non – Destructive	Semi Destructive	Destructive
<ul style="list-style-type: none"> <li>• Barkhausen noise method</li> <li>• X-ray diffraction method</li> <li>• Neutron diffraction method</li> <li>• Ultrasonic method</li> </ul>	<ul style="list-style-type: none"> <li>• Hole drilling method</li> <li>• Ring-core method</li> <li>• Deep-hole method</li> </ul>	<ul style="list-style-type: none"> <li>• Sectioning method</li> <li>• Contour method</li> </ul>

Figure 4. Classification of Residual stresses measuring techniques (Dive et al., 2017)

The semi-destructive method has almost similar principle to the destructive method where the technique indicates to remove only a small amount of material, thus the specimen able to return to its service. Some of the examples of semi-destructive technique are hole-drilling technique, ringcore method (Figure 6) and deep hole method. The study by Šarga and Menda (Šarga and Menda, 2013) was focused on semi-destructive technique where ringcore method and hole drilling technique were compared in order to provide a reliable method in determining the effect of residual stress. Basically, the hole-drilling method was introduced earlier and, a similar derivation is used in the development of ringcore method. Both techniques have almost similarity in discovering the existence of uniform and non-uniform stress through the specimen thickness. The research outcome is stated in Table 1.

It is expected that other researchers will be able to make a decision in selecting a suitable measurement method between these two techniques. The hole-drilling method following the ASTM-E837-13 standard can also be used to measure machining induced residual stresses profile in the face milling 7075-T7451 aluminium alloy (Perez et al., 2018).

On the other hand, the non-destructive method does not involve any material removal or contribute any physical damage in the specimen. The non-destructive method has an advantage in specimen preservation and the measurement can be repeated many times. However, these methods commonly require detailed calibrations on representative specimen material to give required computational data and the process is time consuming (Schajer, 2010).

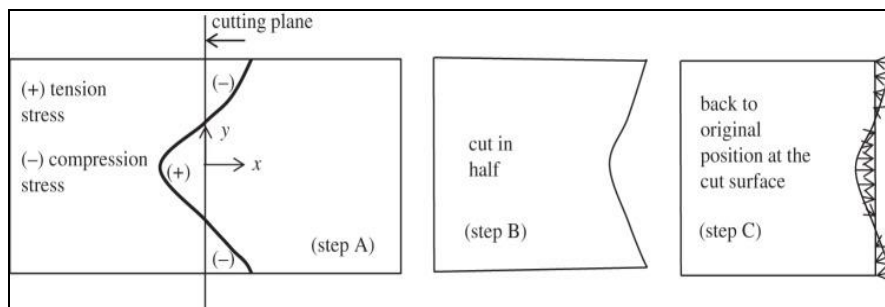


Figure 5. Principle of Contour method (Kartal, 2013)

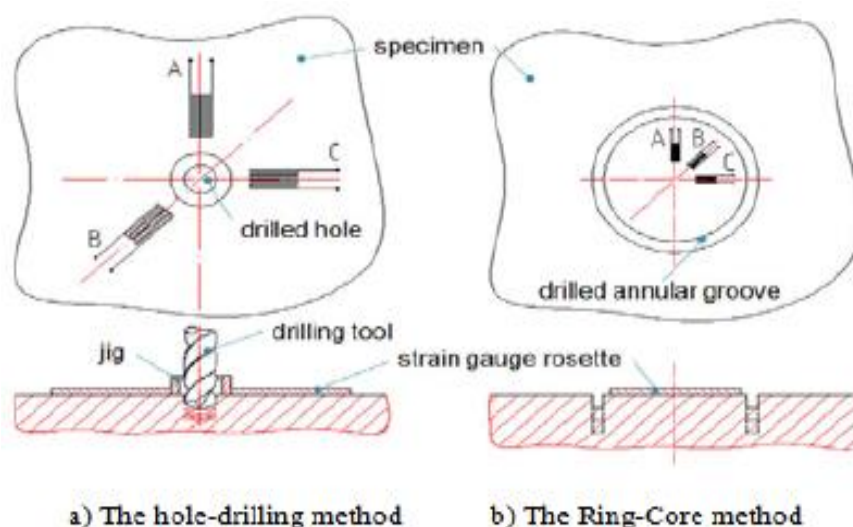


Figure 6. Comparison of the semi-destructive method (a) The hole-drilling method (b)The ring-core method (Šarga and Menda, 2013)

The non-destructive method includes X-Ray Diffraction (XRD) (Jacobus *et al.*, 2000), Moiré interferometer (Andonian and Danyluk, 1985), optical interferometer (Bifano and Hosler, 1993), and neutron diffraction (Robinson *et al.*, 2011). The parameters that homologous to the stress are commonly examined and studied by using these non-destructive techniques.

The XRD method can be used to measure the residual stress on the surface; the x-rays penetrate up to about 10 – 25 μm deep into the surface depending

on the x-ray source and specimen materials. On behalf of that, Walker (Walker, 2001) stated that X-ray diffraction is one of the chosen options when handling very thin specimen because it is capable to measure strains closest to the surface. The selection of stress constant, focusing geometry, location of the diffracted peak, texture, grain size, microstructure, surface conditions and cold-working crystallography have to be considered in order to minimize the error when using XRD to measure residual stress (Prevey, 1986).

Table 1. Comparison of sensitivity, measurability and influence of temperature between ring-core method and hole-drilling method (Šarga and Menda, 2013)

Characterization	Ring-Core method	Hole-drilling method
<b>Sensitive on hole eccentricity</b>	Less sensitive on errors caused by inaccurate location of mill due to the middle of strain gage rosette	More sensitive on errors caused by inaccurate location of drill due to middle of strain gage rosette
<b>Measurability of residual stress</b>	Up to the yield stress	Up to the 0.6 multiple of the yield stress
<b>Influence of temperature</b>	Less sensitive on temperature	More sensitive on temperature



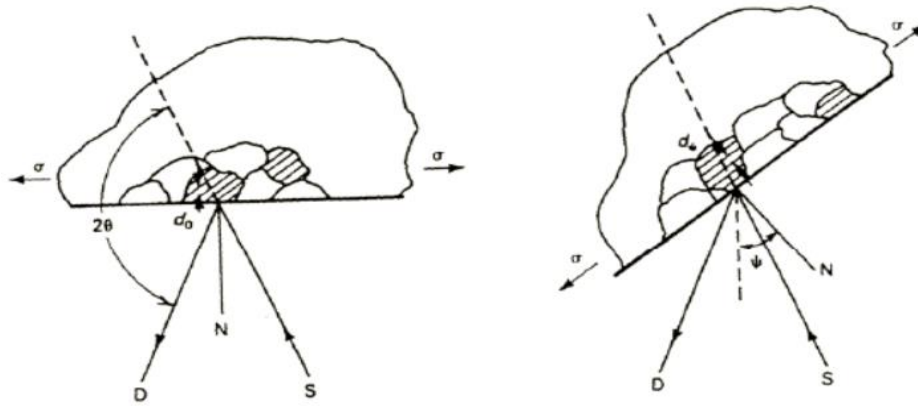


Figure 7. Principles of x-ray diffraction stress measurement; (a)  $\psi=0$ , (b)  $\psi=\psi$  (sample rotated through some known angle  $\psi$ );  $D$  is x-ray detector;  $S$  is x-ray source;  $N$  is normal to the surface (Prevey, 1986)

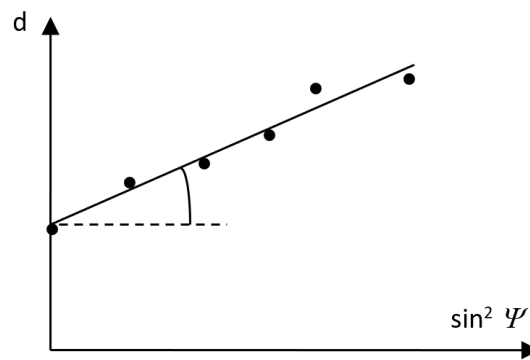


Figure 8.  $d$  vs.  $\sin^2 \psi$  plot.

The principle of the x-ray diffraction residual stress measurement is to measure the strain in crystal lattice and subsequently calculate the residual stress by assuming linear elastic distortion of the crystal lattice (Prevey, 1986). The strain is determined by measuring the different plane spacing ( $d$ ), at different incident angles of x-ray ( $\psi$ ) as illustrated in **Figure 7**. In the stressed sample, the spacing  $d_{hkl}$  varies with crystal orientation and changes with  $\psi$ . Different  $\psi$  angle produces different intensity and peak location which produce different ' $d$ ' values. The stresses can be determined by plotting the ' $d$ ' to  $\sin^2 \psi$  (**Figure 8**).

Residual stress can be determined from the slope of the plot based on the equations (Cullity and Stock, 2001):

$$d = \frac{d_{\psi} - d_0}{d_0} = \frac{1+\nu}{E} \sigma_{\phi} \sin^2 \psi - \frac{\nu}{E} (\sigma_{11} + \sigma_{22})$$

where  $d_{\psi}$  is the spacing of the planes under stress,  $d_0$  is the spacing of the plane in the absence of stress,  $\nu$  is the Poisson's ratio,  $E$  is the Young's Modulus,  $\sigma_{\phi}$  is the residual stress,  $\sigma_{11}$  and  $\sigma_{22}$  are the principle stresses. The equation can be applied with the assumption that the stress at the direction parallel to the surface normal ( $\sigma_3$ ) at the surface is always zero and that only two normal stress components exist at the surface ( $\sigma_1$  and  $\sigma_2$ ). Therefore, X-Ray Diffraction technique is widely used in recent experimental studies for measuring residual stress of the machined workpiece. In general, this

method combines with electrochemical polishing use to measure the residual stress profile across the thickness.

He *et al.* (He *et al.*, 2016) evaluated the effect of cryogenic in turning Inconel 718 by measuring the distribution of residual stress across the depth of machined workpiece by using X-ray Diffraction and electro-polishing methods to remove the workpiece layer by layer. Wang *et al.* (Wang *et al.*, 2017) also used X-Ray Diffraction method combined with electropolishing removal process to study the near-surface and sub-surface residual stresses profile of machined Inconel 718 produced by ball end milling. Kuczmaszewski *et al.* (Kuczmaszewski *et al.*, 2018) have studied the state of stresses in half-finished product and in samples after machine cutting for rolled AW-2024 and AW-7075 aluminium alloys using combination of X-Ray Diffraction and electrochemical polishing. In addition, Turan *et al.* (Turan *et al.*, 2019) measured the residual stress by strain gauge and X-ray diffraction methods in different shaped of rails. According to their studies, the strain gauge is more suitable to measure residual stress for bigger specimens compared to X-ray diffraction.

Another non-destructive measurement method is ultrasonic measurement method. This method is based on the acoustic-elasticity effect, according to which the velocity of elastic wave propagation in solids is dependent on the mechanical stress (Kudryavtsev, 2008). The waves are launched by a transmitting transducer, propagate through a region of the material, and are detected by a receiving transducer (Kudryavtsev, 2008). This measurement technique can be utilized for measuring residual stress on thick

samples. However, there are not many reports on the used of ultrasonic measurement method used for measuring residual stress of the machined workpiece. It is reported that the ultrasonic  $V_{(z)}$  method and X-Ray diffraction method show comparable results when measuring the residual stresses of complicated shape components such as aeroengine blade fabricated by ball-gun shooting (Xiang *et al.*, 2018). The ultrasonic measurement method is widely used for measuring residual stress in the welded part.

Based on Walker (Walker, 2001) study, there are other approaches to detect the presence of residual stress in a system, which is much more convenient such as strain gage cut-ups, chemical etching technique that shows the imaging of the residual stress through microstructure analysis, microhardness mapping and others. The microhardness mapping profile can be used to indicate the presence of plastic deformation profile across the thickness even though there are some others limitation on this convenient approach where a repetition experimental must have a reliable result. According to Lu *et al.* (Lu *et al.*, 2016), the hardness is high near the machined surface and gradually decreased toward the depth in high speed cutting of AZ31 magnesium alloy. In addition, the high cutting speed produced lower hardness near the machined surface.

#### 4. MACHINING INDUCED MICROSTRUCTURAL CHANGES

In addition to the residual stress measurement methods discussed in the previous section, the deformation produced by machining process can also be characterized by its metallurgical changes such as the change in the microstructures

(To *et al.*, 2008) or crystal orientations (To *et al.*, 2003). These methods can also give faster and less expensive analysis to characterize the effect of machining on the surface integrity of machined workpiece. Microstructural transformations on the machined surface of a Zn-Al alloy have been reported (To *et al.*, 2008)(To *et al.*, 2003); the changes are confined only to the surface of the bulk material machined. Optical microscopy, back-scattered electron microscopy (BSEM), electron back-scattered diffraction (EBSD) and x-ray diffraction techniques (XRD) can be used to analyze the changes in microstructure of surface and sub-surface of the machined results (To *et al.*, 2008).

Microstructural changes in the near-surface have been merely observed and reported in the machining of thick samples made of Al7075 alloy (Campbell *et al.*, 2006) but no further investigations on the nature of change have been made. The recrystallization in the surface and sub-surface indicates the existence of high strain rate (Swaminathan *et al.*, 2007). The plastic strain increases with increasing depth of cut or reducing the rake angle. The grains recrystallization not only occurs in the chips but also at the surface and vicinity of the machined surface of the workpiece. Analysis of both chips and workpiece microstructures indicates that recrystallization occurs as a result of high strains and temperature gradient via dynamic recrystallization (Saldana *et al.*, 2010).

Moreover, there is also an interrelation between residual stress induced by plastic deformation and heat generated during machining of magnesium alloys

AZ31B on microstructure changes and hardness (Zhou *et al.*, 2014).

## 5. CONCLUSION

This study provides an overview of machining induced residual stress, machining parameters effects to residual stress and various residual stress measurement methods. The residual stress induced in the machining process occurs due to thermal and mechanical loading in the chip formation. This paper has highlighted the machining parameters such as depth of cut, cutting speed and feed rate need to be controlled in order to minimize the residual stress especially tensile residual stress. In addition, cutting force and cutting temperature also affected the magnitude and depth of residual stress. The challenge in the measurement of residual stress is to select a suitable measurement method in order to quantify the residual stress on the machined workpiece and to understand the distribution of residual stress profile across the thickness especially just below the machined surface. Each measurement method has its own advantages and disadvantages depending on the purposes, materials, size and the availability of the machined workpiece. Further study should be focused on the prediction of residual stress using prediction model and finite element simulation in order to prevent and analyze the effect of machining parameters on residual stress prior machining. In addition, due to the trend of micro-scale feature components produced by advanced machining process such as micro-scale milling, it is necessary to select the correct measurement method.

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