Chapter 2
Surface Integrity When Machining Metal Matrix Composites

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Abstract Traditional machining operations normally lead to the alterations of surface and subsurface that makes it different from the bulk material. In order to avoid undesirable alterations that may have adverse affect on the quality of the machined components it is essential to know the various types of alteration and their origin. It is also important to know the cutting parameters and tool geometry that will lead to machined components of high-quality.

2.1 Introduction

In spite of the rapid advances being made in the development of new and improved production techniques, such as precision casting, directional solidification, and net shape forming, traditional metal machining processes still feature directly or indirectly in the manufacture of most of the items in our present technological society. It is generally accepted that machining introduces changes into the surface region that makes it different from the bulk materials. As mechanical properties such as fatigue, creep, and stress corrosion cracking are important material properties that are highly surface sensitive, it is important to obtain complete information on the surface characteristics of machined components, in addition to those mechanical and physical properties generally considered essential. It is also important to identify the cutting parameters that will generate a high-quality surface at minimum cost. It has long been evident that the traditional machining

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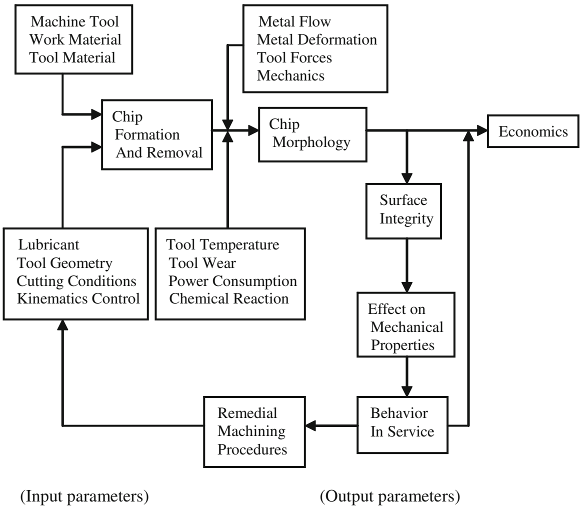

Fig. 2.1 A simplified machining system

process, although conceptually simple, is perhaps one of the most complex of the manufacturing operations employed today. A complete description of the process involves the consideration of an entire system, consisting of various input and output parameters linked together through a variety of complex internal phenomena. A simple scheme showing the relationship between some of the more important parameters involved in machining process is given in Fig. 2.1. A change in any one of the input parameters can lead to a change in all the output parameters.

2.2 Surface Integrity

Researchers in the field of machining have generally accepted the term surface integrity to describe the nature or condition of the machined surface region. It is interpreted as those elements that describe the actual structure of both surface and subsurface [1]. If the surface of a machined component posses integrity, then it is not affected by the action of the machining process used in its fabrication. Conversely, if integrity is lacking, then surface and subsurface damage have occurred as a consequence of the impact of machining process. Surface integrity has two distinct and important aspects, (1) surface topography that describes surface roughness and other features associated with the geometry of the surface, and (2) surface region metallurgy of the layer that is produced by the machining process including the effect of any alterations with respect to base material.

A list of more obvious elements that can be used to describe surface integrity is given in Table 2.1. Clearly, this method of division is by no means unique and other methods could be devised. In addition, not all elements mentioned here can

Table 2.1 Elements of surface integrity

Surface elements	Subsurface elements
Surface roughness, Waviness, Texture, Distortion, Micro-cracks, Macro-cracks, Tears, Laps, Pits, Cavities, Surface corrosion, Intergranular corrosion, Debris, Hardness variations, Surface phase transformation, Surface structural changes, Thermodynamic property changes, Grain boundaries, Stress induced surface roughness, Variation in electrostatic potential, Residual stress	Micro-cracks, Macro-cracks, Phase transformation, Compositional changes, Hardness changes, Plastic deformation, Dislocation density and distribution, Recovery, Recrystallization, Grain growth, Residual stresses, Inclusions, Voids, Vacancies interstitials, Frenkel defects, Solute atoms, Twins, Stacking fault, Antiphase boundaries, Domain walls

be expected in a given material system. Some phenomena referred to are not possible in many materials. For example, domain walls would be expected only in ferro-magnetic or ferro-electric materials. Also, surface and subsurface alterations need not necessarily affect adversely the aforementioned surface sensitive mechanical properties. Indeed some forms of alteration can prove beneficial. For example, the introduction of residual compressive stresses in the surface region of a component can lead to substantial improvement in fatigue life. It is for this reason that critical surfaces are often given post-machining treatments, such as shot peening in order to improve fatigue life.

2.3 Surface Integrity Evaluation Techniques

An excellent early review of techniques for assessing surface integrity is presented in Ref. [2]. Table 2.2 lists a summary of various methods used in identifying various defects produced as a result of machining. In this section a few of the most common techniques used in evaluating the quality of the machined surface region of metal matrix composites namely, optical and scanning electron microscopy of surface and subsurface, plastic deformation of surface and subsurface, residual stress analysis of the surface region, and surface topography will be presented.

2.3.1 Optical and Scanning Electron Microscopy

Optical and scanning electron microscopies of machined surface are commonly used to assess the quality of the machined surface. Machined surfaces are examined using optical microscope at various magnification to investigate the presence of surface damage in the form of cavities, macrocracks, scratch marks, etc.

Table 2.2 Techniques for assessing surface integrity

Interest area	Common techniques	Identifiable defects
Surface topography	Profilometry, Optical microscopy, Interference microscopy, Electron microscopy, Metrology	Surface profile, Surface roughness, Waviness, Lay, Surface defects, Distortion
Surface structure	Visual inspection, Optical microscopy, Dye penetrant, Magnetic particle, Microetch eddy current, Ultrasonic pulse echo, Ultrasonic velocity, High frequency ultrasonic, X-ray spectrography, Radioactive gas penetrant, Surface electrical resistance, Beta backscatter, Electrochemical potential, Microhardness, Deflection-etching	Surface defect, Crack detection, Surface phase transformation, Surface hardness changes, Plastic deformation, Surface residual stress, Surface compositional changes
Surface chemistry	Laser probe mass spectrometry, X-ray spectroscopy, Auger spectroscopy, X-ray microprobe analysis, Transmission electron microscopy	Surface composition
Subsurface structure	Optical microscopy, Eddy current, Ultrasonic pulse echo, X-ray radiography, Gamma radiography, Radioactive gas penetrant, X-ray diffraction, Deflection-etching, Microhardness testing, Scanning electron microscopy, Transmission electron microscopy	Subsurface defects, Phase transformations, Recrystallization, Grain growth, Hardness variations, Inclusions, Residual stresses, Dislocation structures
Subsurface	Chemical analysis, X-ray spectrometry, X-ray diffraction and X-ray microprobe analysis, Auger spectroscopy, Transmission electron microscopy	Subsurface composition

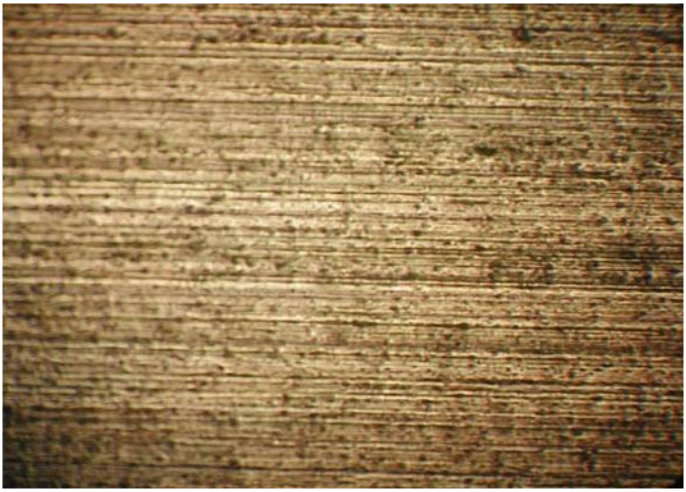

Fig. 2.2 An optical photomicrograph of machined surface (×100), hot-rolled Al/SiC, 20% vol. SiC

Selected samples are then used for detailed analysis and for observing the presence of types of damages that are not possible by using optical microscope such as formation of voids, microcracks, etc. Figure 2.2 is a typical optical photomicrograph of the machined surface showing long grooves parallel to the direction of cutting velocity and pitted area. The equally spaced long grooves are attributed to feed marks caused by the geometry of the cutting tool.

A typical scanning electron photomicrograph of the machined surface is presented in Fig. 2.3. Surface damage in the form of short and long grooves parallel to the direction of cutting, pitted area, and cavities are generally present and randomly occurs when machining metal matrix composites. It is understood that during cutting operation some of the SiC particles are partially or totally detached from the machined surface, and left behind cavities of various sizes and shapes. Some of the detached particles may have passed underneath the tool and were dragged along the surface for a distance and hence resulted in grooves of various lengths. Once again as expected feed marks of the cutting are responsible for the equally spaced long grooves parallel to the direction of cutting velocity. Figure 2.4 is a scanning electron micrograph of the machined surface showing cavity and crushed SiC particles. It has also been observed that the presence of hard particles of SiC in a soft matrix such as aluminum can lead to voids around the silicon carbide particles during the machining operation [3].

Optical and scanning electron microscopy is also used to examine subsurface of the machined components. Figure 2.5 is a scanning electron image of the side surface of the machined surface. From the figure it can be seen that machined surface is irregular. The presence of a micro-crack that initiated at the surface and extended beneath the machined surface is also visible.

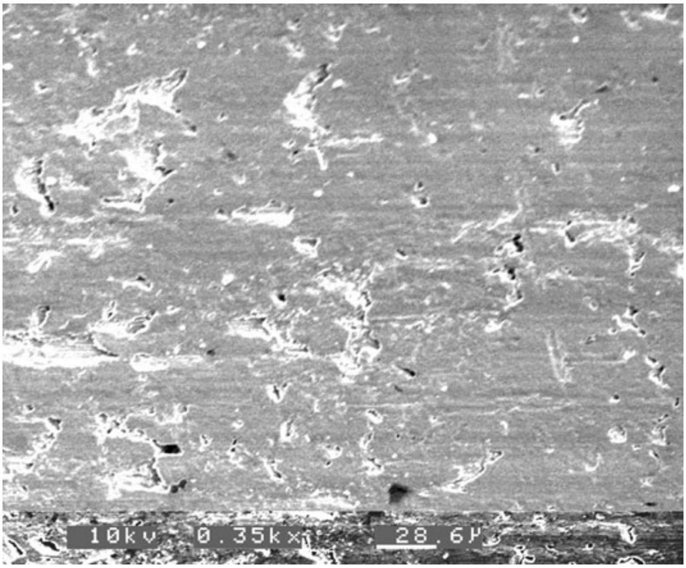

Fig. 2.3 Typical scanning electron micrograph of machined surface, hot-rolled Al/SiC, 20% vol. SiC

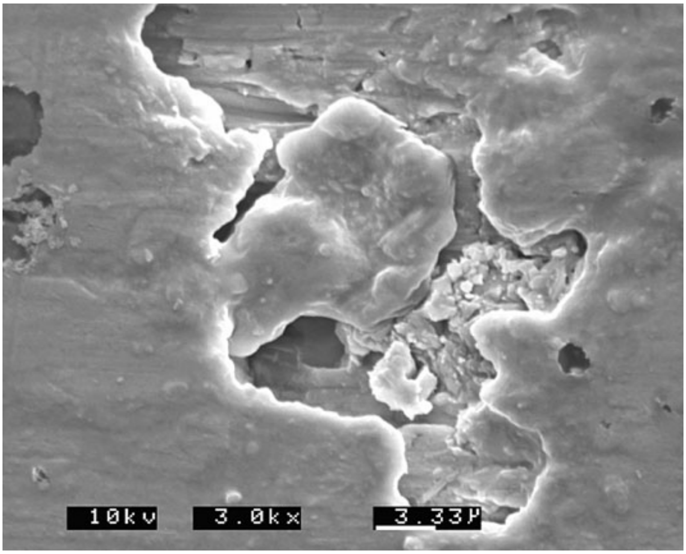

Fig. 2.4 Scanning electron micrograph of machined surface, hot-rolled Al/SiC, 20% vol. SiC

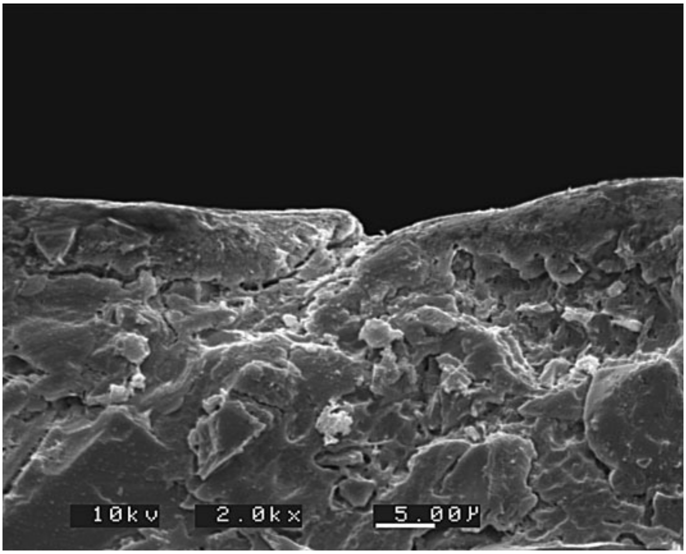

Fig. 2.5 Scanning electron image of the machined subsurface, hot-rolled Al/SiC, 30% vol. SiC

2.3.2 Plastic Deformation Analysis of Surface and Subsurface

Surface region plastic deformation is normally assessed by examining the side surface of the machined specimen that is perpendicular to the machined surface. For this purpose small segments of the test specimen is mounted metallographically in the usual way and then polished and etched to reveal the grain boundaries. Plastic deformation is normally detected from the rotation of grains in the direction of cutting velocity that is visible with the aid of an optical microscope. Macrocracks if present and surface irregularities are also easily detected and observed. Similar observations can be made using scanning electron microscopy. Plastic deformation resulting from the dislocation pile-ups near the machined surface region is detectable using a transmission electron microscope [3]. Microhardness measurements of the surface region (surface and subsurface) are also used to assess subsurface plastic deformation. One of the difficulties in obtaining reliable results is the presence of hard particles of SiC that the indenter may come in contact with, hence will give false reading of the matrix hardness. However, microhardness indentation has been used successfully in the past to evaluate subsurface plastic deformation of machined Al/SiC composites [3].

2.3.3 Residual Stress Analysis of Surface and Subsurface

Residual stress measuring techniques are in general, classified as destructive and nondestructive. The destructive methods such as hole-drilling and deflection-etching involve the destruction of the test samples when evaluating residual stresses. The nondestructive methods that include optical, ultrasonic, electromagnetic, and x-ray diffraction are based on measuring the changes in some physical properties that are caused by the presence of residual stresses. A summary of these techniques is presented in Ref. [4]. Among the nondestructive methods x-ray diffraction may be the most common technique used for measuring residual stresses caused when machining metal matrix composites.

The deflection-etching technique is based on removal of thin layers of stressed material from the machied surface region by electrochemical action. The author of this article has used this technique with great success and hence, it will be discussed further in this section. At this point it will be advisable to know the source of residual stresses in machining.

The source of residual stresses in machining is complex and may be attributed to inhomogeneous plastic deformation caused by mechanical and thermal events associated with the process of chip formation, and the interaction between the tool cutting edge and freshly-machined workpiece surface. Figure 2.6 is a schematic sketch of the residual stress sources and residual stress distribution. The aforementioned sources and their effects are explained as follows. The cutting action of the tool cutting edge and the rubbing or burnishing effect of the tool nose-workpiece contact area may be the leading cause of residual stresses due to mechanical deformation. During the cutting operation, the material ahead of the cutting point experiences compressive plastic deformation and the material behind experiences tensile plastic deformation. If the tensile deformation is more than compressive deformation, the resulting stress is compressive and vice versa [5]. The rubbing and burnishing effect which is similar to surface rolling or shot peening, produces compressive residual stresses. The heating of the surface produces compressive plastic deformation by thermal stresses, then tensile stresses upon cooling. The final state of residual stress distribution in the surface region is the combined effect of the three components [6, 7].

2.3.3.1 Deflection-Etching Technique

Deflection-etching technique was first developed in 1951 [8]. The description of the process and the principle involved is given here. Let us consider a straight metallic bar of rectangular cross-section workpiece having a length of l, a width of w, and a thickness of t. The workpiece is then mounted and clamped and the thickness of the workpiece is reduced by removing a layer of the material using a machining process such as milling, broaching, planing, and grinding. As a consequence of machining residual stresses will be introduced in the surface region of the workpiece that will cause the bar to curve once the bar is unrestrained and removed from the clamping device. The bar may curve concave upward or concave downward (when viewed from the stressed layer) depending on the sign of combined effect of the induced residual stresses as explained in Fig. 2.6. Now if a thin layer of the machined surface is removed by chemical etching this will lead to a partial removal of the stresses that consequently will result in a change in the

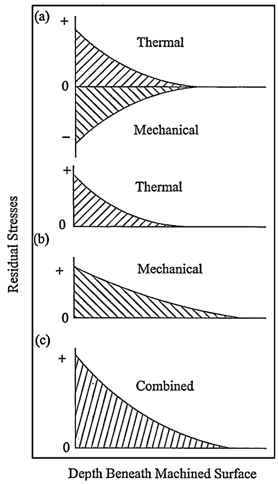

Fig. 2.6 Schematic of residual stress distribution. **a** Rubbing action. **b** Cutting action. **c** Combined effects [6]

radius of curvature of the bar. In this process the remaining residual stresses will be redistributed and a new equilibrium will be established. Theory of elasticity can then be used to determine the stress distribution from the knowledge of the changes in curvature and thickness of the bar due to successive removal of thin layers. A complete analysis of residual stresses for a bar of rectangular cross-section is presented in Ref. [8].

The author of the present article has used a modified deflection-etching technique in evaluating the residual stress distribution in turning operation of ring-shaped metal matrix composites workpieces. A detailed description of the process and the method used in determining residual stress distribution is given elsewhere [9], however, the plot of a typical result is shown in Fig. 2.7. From the figure it can be seen that residual stresses are compressive for the cutting condition and tool geometry used when turning T6-heat treated Al/SiC 20% volume SiC composites test samples. The residual stresses are low at the surface and increase with depth beneath the machined surface. The low residual stresses at the surface may be attributed to relief of stresses due to surface cracking and/or partial or total detachment of hard particles of SiC from the surface as explained previously.

2.3.4 Surface Topography

Laser or stylus type profilometers are normally used to measure surface roughness and to obtain surface profile of the machined surface. The presence of hard particles of SiC in metal matrix composites results in higher surface roughness values when compared with surface roughness of matrix metal using optimum and same cutting conditions. This has been demonstrated by mounting samples of 6061 Al matrix metal and 6061Al/SiC composites having 20 and 30% volume SiC

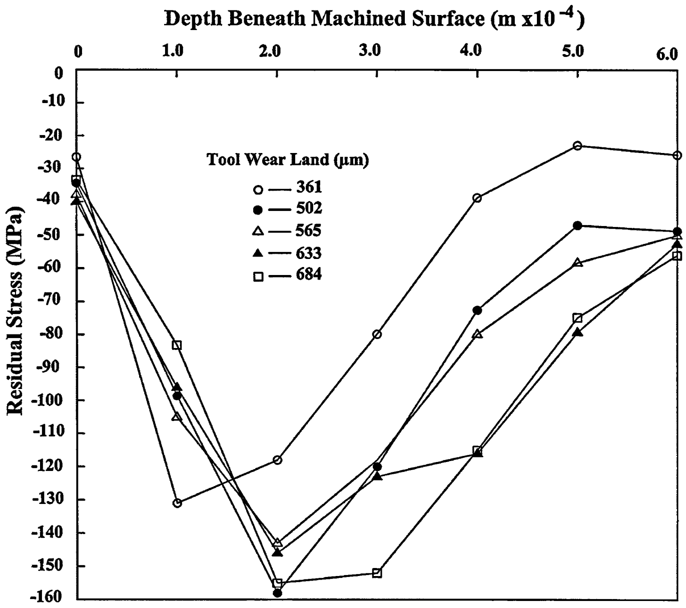

Fig. 2.7 Residual stress distribution—20% vol. SiC—T6 heat treat

reinforcement on the same mounting and then grinding and polishing metallographically in the usual way. The surface roughness of each sample was then measured using a stylus type profilometer and were 0.05, 0.148, and 0.30 μm, respectively, for 6061 Al, 20% SiC, and 30% volume SiC particulates composites. As discussed earlier during machining operation SiC particles are partially or totally removed from the surface and leaving behind cavities of various shapes and depths. Some of these particles are passed underneath the tool flank and dragged by the tool flank along the surface that leads to grooves of various widths and lengths. Therefore, it may not be realistic to anticipate a high-quality surface finish when machining metal matrix composites as it is possible when machining the matrix metal.

2.4 Conclusion

Machining metal matrix composites using traditional cutting methods lead to the damage of surface and subsurface. In general, the severity of the damage is reduced and surface integrity is significantly improved when the cutting speed is increased and the depth of cut and feed rate is decreased. It has been shown that the volume fraction of the reinforcement particles has a great influence on the quality of the machined surface region. The quality of the machined surface improves as the volume fraction of the reinforcement particles is reduced.

Similarly better surface quality can be achieved when the size of the reinforcement particles are reduced. The application of a lubricant does not affect significantly the surface integrity of the machined metal matrix composites. It has also been reported that better surface finish is achieved with whisker reinforced composites as compared with particulate reinforcement composites [10].

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