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Surface Integrity and Roughness of Characterization in Milling Processes

Dr. Md Salim Ansari[1] , Satyam Chakraborty[2], Vishal Kumar Mandal[3],

Sujay Mandal[4], Shahil Raja[5*], Sonu Ray[6] Aryan Kumar Yadav[7]

1 Assistant Professor, K K Polytechnic, Govindpur, Dhanbad, Jharkhand, India.

234567 Department of Mechanical Engineering

K K College of Engineering and Management, Govindpur, Dhanbad, Jharkhand, India.

***Corresponding Author-** Shahil Raja

Abstract:

Precision manufacturing in the aerospace, automotive and medical sectors relies on milling to put the finishing touches on high-performance components. Yet the very nature of the operation is a problem: the cutting tool's edge engages with the workpiece in an aggressive fashion, prompting mechanical, thermal and chemical changes that can leave the finished hardware quite different from what was intended. In this paper we set out to examine the two sides of processed boundaries. On one hand there's surface topography in the form of roughness, lay and spatial patterns; on the other, subsurface metallurgical shifts like residual stress, plastic deformation and variations in microhardness. Through a combination of experimental diagnostics, physics-based characterization and analytical modeling, we show how such things as tool wear, geometry, feed per tooth and cutting speed will modulate the topography. We also make the case for linking macroscopic finish to mechanical properties-fatigue limit and wear among them-in order to provide a sound basis for optimizing both process and structural integrity at the same time.

***Keywords*:** Surface Integrity, Surface Roughness, Milling Process, Machining Parameters

Introduction

Modern engineering, the design specs are becoming ever more demanding, subjecting high-grade metallic materials to higher loading cycles and less forgiving environments. Whether it's a turbine blisk or an aerospace bulkhead, a structural node in an automobile or a biomedical implant, these parts have to be reliable and resist fracture over the long term. The surface boundary layer is where the action is. And while there's a wide array of subtractive technologies available, milling is still indispensable for its speed and the geometric freedom it affords, be it peripheral, end or face work.

For the most part, old ways of thinking in manufacturing would judge a milling job by whether it met the geometric tolerances and looked smooth enough to the eye. But take a high-speed or forceful cut and you get intense mechanical forces and heat that don't stay on the surface. They penetrate the sub-surface matrix for hundreds of micrometers and create what is known as an Altered Material Zone (AMZ). Field and Kahles put a name to these multidimensional effects back in 1964 with the following definition:

"Surface integrity is the unimpaired or enhanced surface condition or properties of a material resulting from a controlled manufacturing process. It involves two distinct aspects: surface topography, which describes the outer micro-geometry, and surface metallurgy, which examines the microstructural variations and alterations occurring immediately below the physical surface." (*Field, M., and Kahles, J. F., 1964)*

Evaluating a machined component requires an understanding of how the configuration of cutting tools, kinematic arrangements, and material properties interact to form unique surface signatures. In this context, the paper presents an exhaustive study of surface integrity and the characterization of surface texture in modern milling operation

Surface Topography and Roughness Characterization

a) Foundations of Topography

Surfaces produced by milling operations exhibit complex geometrical arrangements which are a combination of path profiles, tool micro-geometries and structural variations of the machine milling system. Ideally during milling, the combination of the rotational movement of the milling tool and the translational movement of the workpiece results in the production of a surface with a texture which is periodically arranged and referred to as feed marks or waviness. In milling operations using end and face milling cutters, the dominant form of surface topography is associated with the tool nose radius and the feed per tooth.

Nevertheless, real-world machining can't be described purely with simplified kinematics. Specific microscopic structures in the workpiece, like grain boundaries, secondary hard phases, and inclusions, can cause changes in the mechanism of chip formation. Also, the minimum chip thickness can cause sliding or plowing instead of a continued shear. In this instance, the plowing causes a huge change in the surface profile, with micro-voids and significant plastic deformation.

b) Surface Roughness

Surface Roughness and Surface Texture

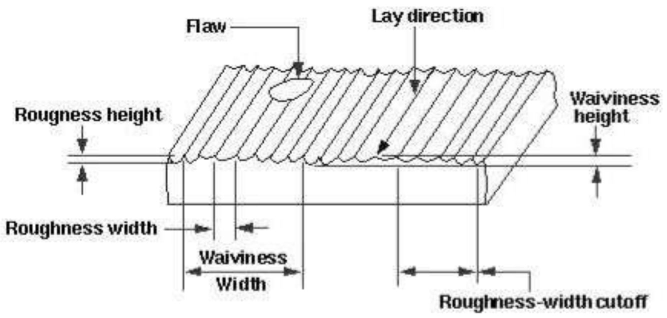
Surface roughness is the presence of irregularities across the surface that can be caused by various machining processes. This, combined together, can be described as surface texture. Every surface on a component contains texture, and this texture is dependent on the method of manufacturing. Various machining processes can produce an abundance of different techniques, and surface texture is formed by the presence of surface deviations.

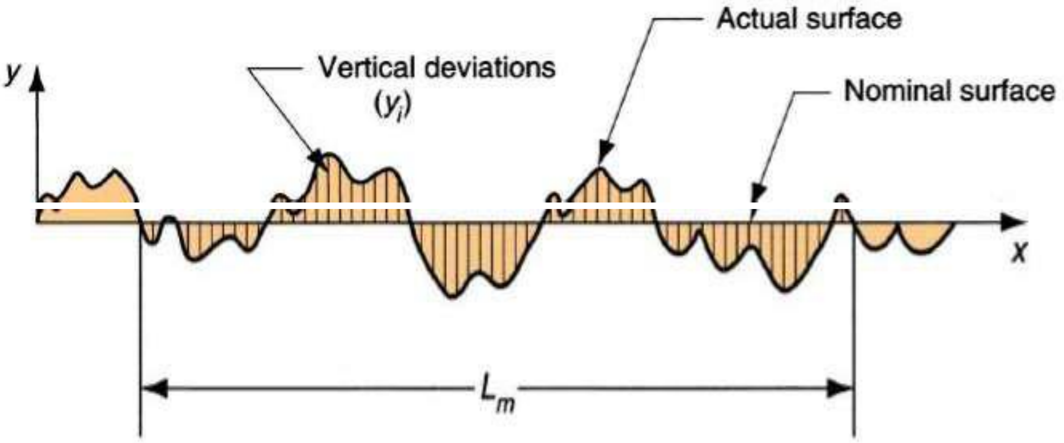
The international standards for surface roughness sort deviations by order. Surface roughness covers third to sixth-order deviations from the ideal surface. The first and second orders are a bit different—they're about the bigger-picture shape, like how flat or round something is (that’s form), and waviness, which usually comes from things like machine tool errors, part deformation, bad setups, vibrations, or even flaws in the material itself. Now, the third and fourth orders get into the finer details—think of periodic grooves or tiny cracks—mostly caused by things like the sharpness and shape of the cutting edge, how the material chips away, or how the cutting process moves. Then you have fifth and sixth-order deviations. These dive right down to the material’s structure, like tiny shifts on the grain or atomic level, which happen because of things like slipping, chemical diffusion, oxidation, or residual stresses within the material. All these different orders stack up on top of each other and make up the final surface roughness profile you see on a finished part.

Figure 1.9, 1.10 can be broken down into three main categories: Surface roughness, Waviness and Form.

Roughness: Perfect smoothness doesn’t really exist, and honestly, it’s not even something we always want. The main thing that shapes a surface’s texture is its roughness—those tiny, closely packed imperfections you feel or see. That’s surface roughness. Now, there’s something else called waviness. Waviness is about bigger, repeating bumps or dips on the surface, which usually come from structural issues or the machine itself. These irregularities are more spaced out than roughness.

Lay : Then there’s lay. That’s the pattern you get from the way the machining tool moves—like horizontal, vertical, or maybe even circular lines left behind. Different machining methods create different lays.





Flaws: Flaws are the odd defects you spot once in a while—cracks, scratches, bits of material that don’t belong, that sort of thing. Flaws tie into surface texture, but they also mess with the overall integrity of the surface. If you want to predict how a part will behave or if you need to fine-tune the manufacturing process, you have to measure and define these surface qualities. That’s where surface texture parameters come in.

c) Primary spatial and amplitude Roughness Parameters

Surface topography characterization is based on statistical amplitude metrics that translate complex surface traces into accurate numerical indicators. The arithmetic average roughness (Ra) is a commonly used parameter for manufacturing floors but it has some fundamental limitations. It does not distinguish between a surface with sharp, isolated peaks and a surface with deep, narrow valleys. Robust characterization thus requires a complete suite of amplitude parameters:

$$R_a = \&\text{frac1100;} \int 0\ L\ |z(x)|\ dx \tag{1}$$

$$R\ q = \surd\&\text{frac1100;} \int 0L\ z2(x)\ dx \tag{2}$$

where L is the sampling evaluation length and z(x)vertical profile deviations with respect to the reference mean line. Standard practice to more clearly delineate contact mechanics and wear performance involves inclusion of skewness (R_{sk}) (an indicator of the symmetry of the profile) and kurtosis (R_{ku}) (a measure of the sharpness of the profile transitions.

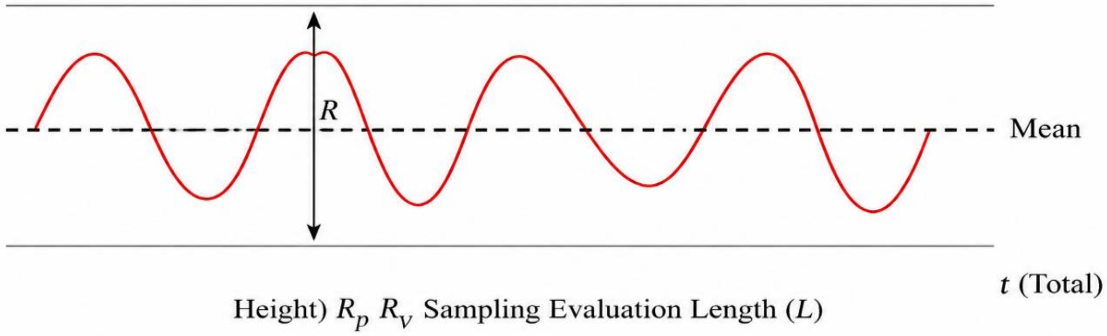


Figure 1. Schematic decomposition of a machined surface profile track illustrating primary amplitude deviations relative to the arithmetic mean reference.

In the era of functional surface modeling, the classical 2D linear track-based extraction is gradually complemented by 3D areal surface topographic parameters (Sa, Sq, Ssz) as defined by ISO 25178. Areal diagnostics maintain spatial frequency distributions, thereby enabling engineers to monitor directional lay signatures and localized microstructural defects often missed by line profiles.

Subsurface Metallurgical Integrity and Microstructural Alterations

a) Plastic Deformation Zones and Altered Layers

The mechanical stress tensor in the primary, secondary and tertiary cutting zones exceeds regularly the yield strength of the workpiece material during a common milling process. The cutting tool edge acts as a hard indenter, creating a severe plastic deformation in the subsurface boundary layer. This localized structural deformation stretches and reorients grains in the direction of the tool cutting path.

In traditional cutting actions where tool contact occurs, improper parameters—such as excessive tool wear, high feed rates, and inadequate lubrication chemistry—severely deform the surface integrity, creating micro-cracks, deep phase changes, and rapid intergranular damage." *Degarmo, E. P., Black, J. T., and Kohser, R. A. ,2003)*

High thermal energy is combined with a plastic strain to initiate the recrystallization of the microstructure in high-speed milling of advanced materials like titanium alloys (e.g. Ti-6Al-4V) or nickel-based superalloys (e.g. Inconel 718). In extreme thermal conditions local temperatures may exceed the material's phase transition point. Then, when the area is quenched, either by rapid heat dissipation into the bulk material or by application of coolant, a change in structure takes place. This appears in ferrous alloys as a hard and brittle untampered martensitic phase, which is usually described in metallographic examinations as a "white layer", because it is resistant to etching in optical microscopy.

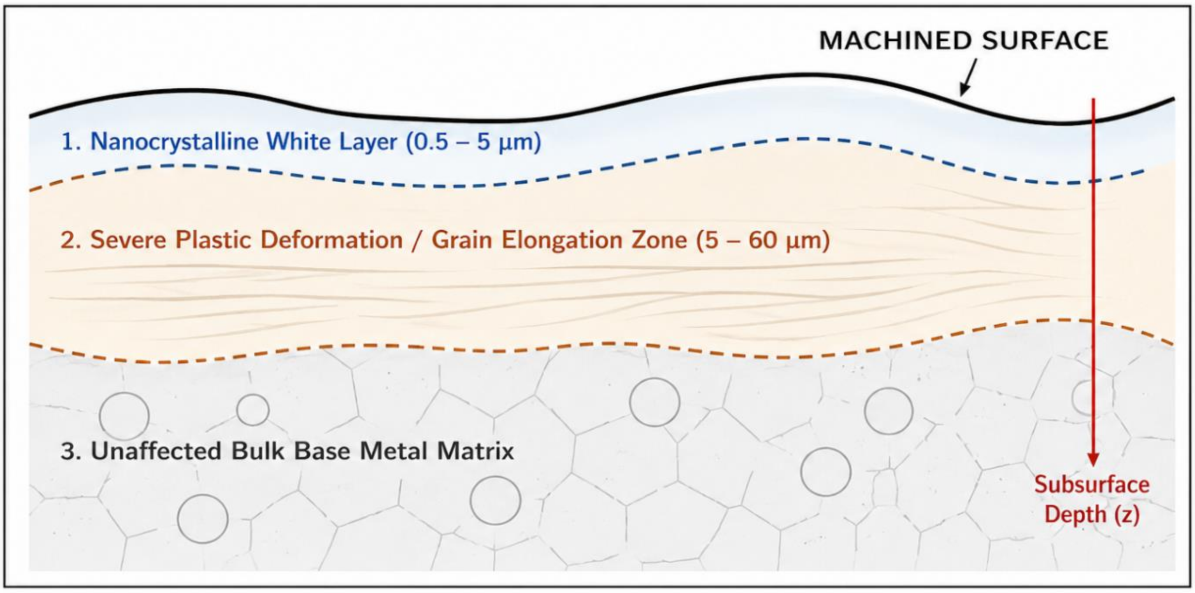


Figure 2. Visual profile cross-section displaying metallurgical stratification zones occurring below the milled surface layer.

b) Microhardness Stratification Profile

You know what? the microhardness profile along the vertical subsurface axis is characterized by a significant stratification, which is a direct consequence of the grain refinement and thermal phase transformations. Depending on the competition between mechanical strain hardening and thermal recovery or over aging, two main subsurface microhardness signatures are usually obtained:

1. **Work-Hardening Dominated Stratification:** The microhardness shows spikes at the immediate surface boundary layer in the case of operations dominated by mechanical crushing forces and falls gradually to merge with the bulk material hardness. Such a trend is typical for milling operations at low cutting speeds with sharp tools.
2. **Thermal Softening / Over aging Stratification:** The immediate subsurface layer can soften structurally or overage where heat generation exceeds the mechanisms for plastic deformation. This results in a localized microhardness deficit beneath the tool contact zone before returning to baseline levels deeper within the component core.

To quantitatively evaluate these profiles, automated micro-Vickers or nanoindentation hardness matrices are sampled along polished cross-sections. This allows engineering teams to construct precise profiles that accurately map process parameter influences against physical properties, as outlined in **Table 1**.

Table 1: Process Variable Manifestation on Machined Subsurface Attributes.

Milling Parameter State PDF	**Topographical Footprint PDF**	**Microstructural State (AMZ) PDF**	**Microhardness Impact PDF**
Sharp Cutting Edge, High V_C, Low f_Z	Low Roughness, Regular Feed Marks	Minimal Altered Depth (<5 μm)	Stable Baseline, Slight Hardening
Flank Wear (V_B > 0.3 mm)	High R_a, Surface Micro-Voiding	Thick White Layer Generation	Extreme Near-Surface Spiking
Dry High-Feed Roughing	Severe Surface Tearing, High R_z	Deep Plastic Deformation Lines	Subsurface Softening Gradient

Mechanical Residual Stress Fields

a) Physical Mechanisms of Stress Generation

Residual stresses are the stable elastic internal stress fields that remain within a solid structure after all external mechanical loads and thermal gradients are removed. In milling operations, these fields are generated by three coupled physical mechanisms:

- Mechanical Stress Gradients: The tool edge plastically stretches the outermost layer of material. As the cutter moves past, the underlying elastic bulk material attempts to pull this deformed region back to its original volume, establishing a localized compressive residual stress field.
- Thermal Expansion Gradients: High localized temperatures cause the outer material layer to thermally expand. Because this expansion is constrained by the cooler bulk material beneath, the surface layer plastically yields under compression. Actually, when the cutting zone cools back to ambient temperature, this region contracts, leading to an unwanted tensile residual stress field.
- Phase Transformation Volumes: Let me tell you, structural alterations involving volume changes (such as the transformation from austenite to martensite) introduce localized expansion or contraction stress states within the matrix.

b) Analytical Stress Profile Distribution

The net residual stress distribution across a component is determined by the balance between mechanical and thermal energy inputs. High cutting speeds combined with high flank wear generate steep tensile profiles at the surface. Conversely, optimized tool configurations that use clean mechanical shearing can introduce deep compressive residual stress zones. Compressive stress states are highly desirable in critical components because they inhibit micro-crack propagation and dramatically improve resistance to high-cycle fatigue failure modes.

Influence of Milling Parameters on Surface Integrity

a) Kinematic Cutting Parameters (Speed, Feed, and Depth)

Selecting cutting parameters represents a primary mechanism for controlling surface integrity on the factory floor. The feed per tooth (f_z) directly modulates the peak-to-valley height of theoretical feed marks. Increasing f_z leads to a proportional increase in macro-roughness measurements. Though, at low feed rates, the uncut chip thickness can drop below the cutting-edge radius, shifting the tool from an efficient shearing action to an aggressive plowing or rubbing regime that accelerates tool wear and degrades surface quality.

Cutting velocity (V_c) influences surface integrity primarily by altering the temperature field within the shear zones. Elevating V_c decreases the material's yield strength through thermal softening, which can suppress the formation of a Built-Up Edge (BUE) and result in a cleaner surface finish. But, excessive cutting speeds generate high thermal signatures that expand the Altered Material Zone (AMZ), potentially introducing tensile residual stresses and dangerous micro-cracking across the finished profile.

b) Cutting Tool Edge Geometry and Wear Kinematics

The geometric design of the cutting edge, defined by rake angle, clearance angle, and tool nose radius, strongly dictates force distribution and chip flow. A large nose radius provides a geometric smoothing effect that can reduce arithmetic roughness (Ra). Yet, it also increases the contact area, which elevates the mechanical forces transferred into the workpiece subsurface.

As milling tools degrade during service, progressive flank wear (V_B) and crater wear modify the sharp cutting edge into a flattened geometry. This wear land drastically increases friction and rubbing actions, causing rapid thermal spikes and severe mechanical deformation. therefore, managing tool wear cycles is essential for maintaining consistent surface integrity across high-precision production runs.

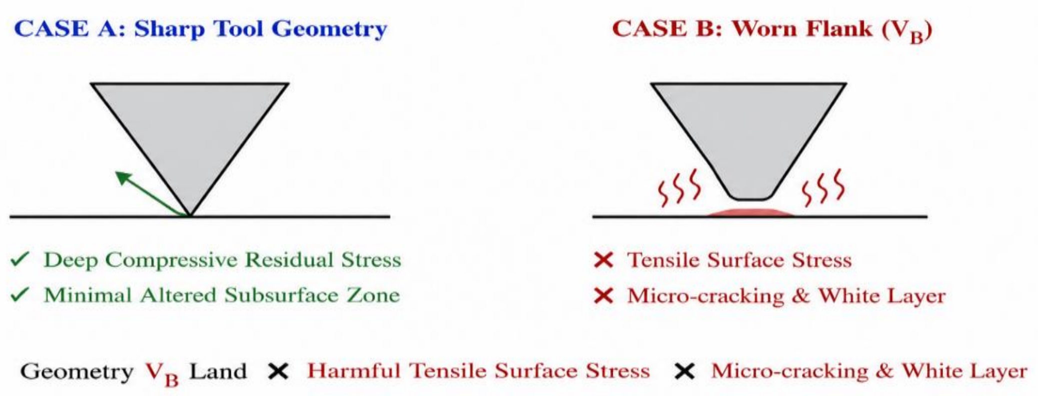


Figure 3. Comparison of tool cutting actions: Sharp edge producing clean shearing vs. worn edge causing excessive rubbing and thermal damage.

Advanced Diagnostic and Metrology Techniques

a) Topographical Measurement Instruments

Accurately quantifying surface topography requires a thorough suite of contact and non-contact metrology tools. Traditional contact stylus profilometers track surface variations by drawing a diamond tip across the profile. While reliable and standardized, this approach is limited by the physical radius of the stylus tip and risks scratching sensitive materials.

To overcome these limitations, advanced manufacturing facilities increasingly apply optical non-contact metrology tools. The truth is, coherence scanning interferometry (CSI) and confocal laser scanning microscopy (CLSM) provide rapid, nanometer-scale 3d surface reconstructions. These optical methods capture high-resolution areal data, enabling detailed mapping of complex milling textures and localized defects.

b) Subsurface Metallurgical Diagnostics

Characterizing the subsurface Altered Material Zone (AMZ) requires destructive metallographic preparation combined with high-resolution microscopy. Cross-sections are cut, mounted, and polished to a mirror finish before being etched with chemical agents (such as Nital or Kroll’s reagent) to reveal grain boundaries and phase distributions under Optical Microscopy (OM) or Scanning Electron Microscopy (SEM). Residual stress fields are typically quantified using non-destructive X-ray Diffraction (XRD) via the $\sin^2 \boldsymbol{\psi}$ method, which monitors lattice strains to calculate internal stress distributions. Let me tell you, when deeper stress profiles are required, incremental electropolishing is used to expose underlying layers for sequential measurement.

Functional Implications of Surface Integrity

The surface topography and sub-surface properties produced during milling directly govern the final component's operational performance and resistance to in-service failure. In cyclic loading environments, fatigue life is highly sensitive to surface quality. Surface roughness valleys function as localized stress risers that accelerate micro-crack initiation. If the surface layer also contains tensile residual stresses, crack propagation is accelerated, significantly reducing the component's fatigue life.

Conversely, optimizing the milling process to introduce deep compressive residual stress layers helps arrest micro-crack growth, enhancing structural reliability. Here's what I found tribological properties, such as wear resistance and friction performance, are similarly governed by surface characteristics. A balanced topography with controlled skewness ($R_{sk} < 0$) optimizes oil retention capabilities, reducing friction and extending the operating life of sliding mechanical interfaces.

8. Conclusion

This paper evaluated the interrelated factors of surface integrity and topography characterization within modern milling processes. Experimental data and analytical modeling demonstrate that surface finish extends far beyond simple macro-roughness measurements. The structural reliability of machined components is governed by a complex combination of surface topography and sub-surface metallurgical attributes, including microhardness variation, plastic deformation, and residual stress states.

As industries transition toward high-performance materials and tighter design tolerances, traditional trial-and-error optimization is no longer sufficient. Achieving consistent, high-quality manufacturing requires the integration of advanced 3D areal metrology, physics-informed process monitoring, and rigorous tool wear management. By establishing clear relationships between cutting parameters and surface properties, engineering teams can optimize milling operations to maximize production throughput while ensuring exceptional field performance and structural longevity.

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