Reliability of high-strength components subjected to severe functional conditions is known to be greatly dependent on the quality of machined areas. Fatigue failures almost always nucleate on or near the surface. Enter—process control for surface integrity.

a new parameter of process control...

surface integrity can affect reliability of your high-strength parts

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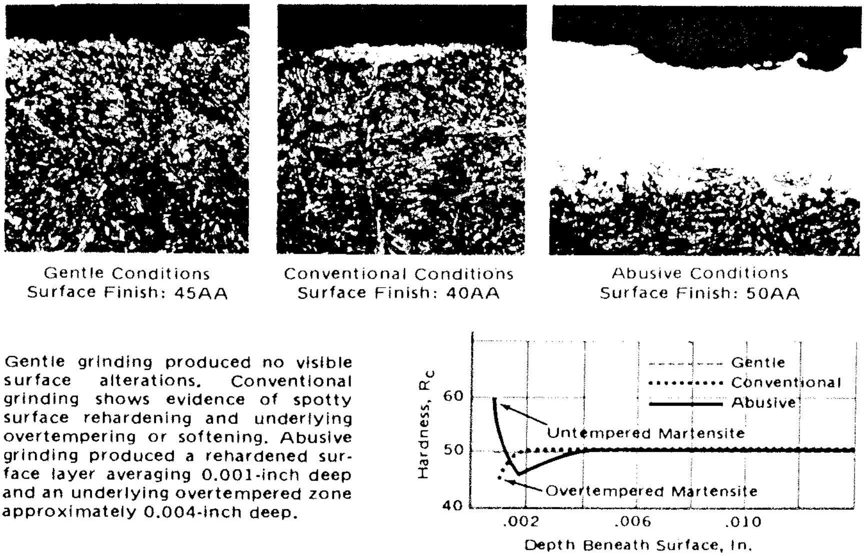
The quality of a machined surface is becoming more and more important in satisfying the increasing demands of performance and reliability. Aerospace structures, for example, are being subjected to more severe conditions of stress, temperature and hostile environments while, at the same time, section size is decreasing due to demands for weight reduction.

Modern production methods, both conventional and electrically assisted, have been developed to process the highest strength and high-temperature alloys which have evolved in recent years. As these high-performance materials have become more difficult to machine, advanced designs have necessitated closer dimensional control. The difficulty in working these high-strength materials and the sensitivity of component surfaces inherent in many processing operations brings the need for careful attention to finished surfaces critically into focus.

What Is Surface Integrity?

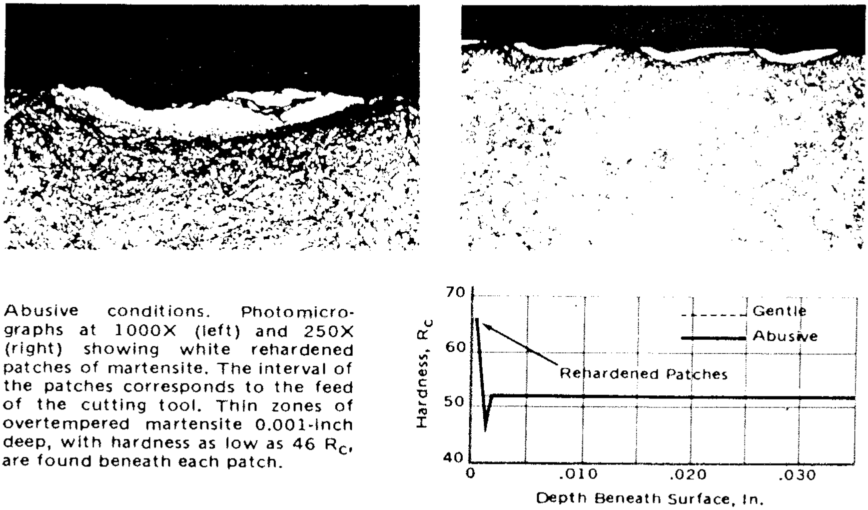
Surface integrity has two important parts. First is surface texture which is a measure of surface roughness or topography. Second is surface metallurgy which is a study of the nature of the surface layer produced in machining. Both aspects are important because, in many cases, they control the strength and performance of structural components.

Surface integrity can be defined as the inherent or enhanced condition of a surface produced by machining or other generating operation. When a component is machined, the surface



Gentle grinding produced no visible surface alterations. Conventional grinding shows evidence of spotty surface rehardening and underlying overtempering or softening. Abusive grinding produced a rehardened surface layer averaging 0.001-inch deep and an underlying overtempered zone approximately 0.004-inch deep.

Fig. 1. *Surface characteristics of AISI 4340 (quenched and tempered, 50 R_c) produced by grinding.*



Abusive conditions. Photomicrographs at 1000X (left) and 250X (right) showing white rehardened patches of martensite. The interval of the patches corresponds to the feed of the cutting tool. Thin zones of overtempered martensite 0.001-inch deep, with hardness as low as 46 R_C, are found beneath each patch.

Fig. 2. *Surface characteristics of AISI 4340 (quenched and tempered, 52 R_C) produced by face milling.*

TABLE 1/Summary of possible surface alterations encountered by metal removal processes

	Conventional Metal Removal Methods		Nontraditional Removal Methods	
	Milling, Drilling or Turning	Grinding	EDM	ECM & CHM
Steels				
Nonhardenable (1018)	Roughness Plastic Deform. Laps and tears	Roughness Plastic Deform.	Roughness Microcracks Recast metal	Roughness Selective etch Intergranular attack
Hardenable (alloy) (4340) (D6ac)	Roughness Plastic Deform. Laps and tears Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Plastic Deform. Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Microcracks Recast Metal Untemp. Mart. Overtemp. Mart.	Roughness Selective etch Intergranular attack
Tool steel, D2	Roughness Plastic Deform. Laps and tears Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Plastic Deform. Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Microcracks Recast metal Untemp. Mart. Overtemp. Mart.	Roughness Selective etch Intergranular attack
Stainless (martensitic) (410)	Roughness Plastic Deform. Laps and tears Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Plastic Deform. Microcracks Untemp. Mart. Overtemp. Mart.	Roughness Microcracks Recast metal Untemp. Mart. Overtemp. Mart.	Roughness Selective etch Intergranular attack
Stainless (austenitic) (302)	Roughness Plastic Deform. Laps and tears	Roughness Plastic Deform.	Roughness Microcracks Recast metal	Roughness Selective etch Intergranular attack
Precipitation hardening (17-4PH)	Roughness Plastic Deform. Laps and tears Overaging	Roughness Plastic Deform. Overaging	Roughness Microcracks Recast metal Overaging	Roughness Selective etch Intergranular attack
Maraging (18% Ni) (250 Grade)	Roughness Plastic Deform. Laps and tears Resolutioning Overaging	Roughness Plastic Deform. Resolutioning Overaging	Roughness Recast metal Resolutioning Overaging	Roughness Selective etch Intergranular attack
Nickel and cobalt base alloy				
Inconel 718, René 41, HS 31, IN 100	Roughness Plastic Deform. Laps and tears Microcracks	Roughness Plastic Deform. Microcracks	Roughness Microcracks Recast metal	Roughness Selective etch Intergranular attack
Titanium alloy				
Ti-6A1-4V	Roughness Plastic Deform. Laps and tears	Roughness Plastic Deform. Microcracks	Roughness Microcracks Recast metal	Roughness Selective etch Intergranular attack
Refractory alloy				
Moly TZM	Roughness Laps and tears Microcracks	Roughness Microcracks	Roughness Microcracks	Roughness Selective etch Intergranular attack
Tungsten (pressed and sintered)	Roughness Laps and tears Microcracks	Roughness Microcracks	Roughness Microcracks	Roughness Selective etch Microcracks Intergranular attack

Abbreviations:
Plastic Deform– Plastic Deformation
Untemp. Mart.—Untempered Martensite
Overtemp. Mart.—Overtempered Martensite

may contain metallurgical alterations. They are generally shallow, usually 0.0002 to 0.006 inch deep.

Types of Surface Alterations

Surface alterations associated with conventional and nonconventional metal removal practices include the following types:

1. Plastic deformation resulting from hot or cold working.
2. Tears, laps and crevice-like defects associated with the "built-up edge" produced in machining.
3. Recrystallization.
4. Changes in the surface layer hardness.
5. Phase transformations.
6. Intergranular attack and preferential solution of microconstituents.
7. Microcracking and macrocracking.
8. Residual stress distribution in the surface layer.
9. Embrittlement by chemical absorption of elements.
10. Spattered surface deposition of remelted metal during electrical discharge, electron beam or laser machining.

Possible surface alterations encountered in both conventional and nontraditional metal removal methods are summarized in Table 1.

Conventional Machining Operations

A variety of surface layer changes can occur as a function of *gentle* versus *abusive* machining. In chip removal operations the term gentle can be applied to those employing machining conditions that provide long tool life and use a *sharp* tool. Abusive chip removal conditions, in contrast, are those in which a *dull* tool is used.

In surface grinding, *gentle* conditions relate to those in which the grinding wheel is kept sharp, while *abusive* conditions relate to those which promote wheel dulling. There are four parameters which affect gentle or abusive grinding: wheel grade, wheel speed, downfeed and grinding fluid. Gentle and abusive conditions in surface grinding and face milling of steel and titanium are indicated in Tables 2 and 3.

Important surface alterations resulting from grinding 4340 steel, 50 Rc, are illustrated in Fig. 1. Using gentle conditions, as in Table 2, no metallurgical alterations were present. When abusive grinding conditions were employed, however, a 0.001-inch deep untempered martensite layer was produced. Below this layer was an overtempered martensite zone approximately 0.004 inch deep. The untempered martensite had a hardness of 60 Rc, while the overtempered zone had a reduced hardness of 46 Rc.

Under conventional grinding conditions a shallow untempered martensite zone was produced by overheating. Abusive drilling and milling (Fig. 2) of 4340 steel, 50 Rc, also tended to yield an untempered martensite zone with an underlying overtempered area.

The presence of either untempered or overtempered martensite on the

TABLE 2/ Surface Grinding Conditions

	Maraging Steel 50 R_c		4340 Steel 50 R_c		D6AC Steel 50 R_c		Ti-8Al-1Mo-1V 35 R_c	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Wheel Type	A46HV	A46MV	A46HV	A46MV	A46HV	A46MV	C60HV	A46MV
Wheel Speed, ft./min.	2000	6000	2000	6000	2000	6000	2000	6000
Cross Feed, in./pass	.050	.050	.050	.050	.050	.050	.050	.050
Table Speed, ft./min.	40	40	40	40	40	40	40	40
Downfeed, in./pass	L.S.*	.002	L.S.	.002	L.S.	.002	L.S.	.002
Grinding Fluid	HCO**	Dry	HCO	Dry	HCO	Dry	HCO	Dry

Machine: Norton 8" x 24" Hydraulic Surface Grinder
Total Stock Removed = .010"

* "L.S." Down Feed: .008" stock removed at .0005 in./pass
last .002": .0004, .0004, .0002, .0002
.0002, .0002, .0002, .0002

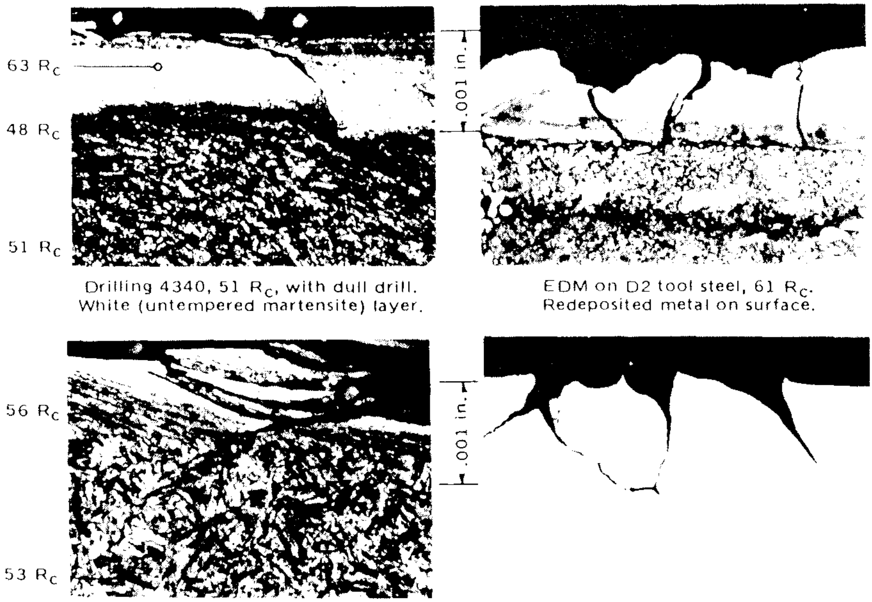
** HCO = Highly chlorinated oil

TABLE 3/ Face Milling Conditions

	Maraging Steel 50 R_c		4340 Steel 50 R_c		D6AC Steel 50 R_c		Ti-8Al-1Mo-IV 35 R_c	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Cutter Axial Rake, deg.	-15	-15	3	3	3	3	10	10
Cutter Radial Rake, deg.	-7	-7	-18	-18	-18	-18	0	0
Tool Material (carbide)	C-2	C-2	C-6	C-6	C-6	C-6	C-2	C-2
Feed per Tooth, in.	.005	.005	.005	.005	.005	.005	.005	.005
Cutting Speed, ft./min.	180	180	150	150	150	150	350	350
Tool Flank Wear, in.	0-.004	.045-.050	0-.004	.045-.050	0-.004	.045-.050	0-.004	.045-.050

Machine: No. 2 Cincinnati vertical high-speed dial type miller
Cutter: 4" dia., single-tooth face mill;
45° corner angle; 5° clearance

Depth of Cut: .010"
Width of Cut: 3/4"
Cutting Fluid: None



Drilling 4340, 51 R_c, with dull drill. White (untempered martensite) layer.

EDM on D2 tool steel, 61 R_c. Redeposited metal on surface.

Reaming 4340, 53 R_c, with dull reamer. Tears from built-up edge.

ECM of Waspaloy, aged, 40 R_c. Intergranular attack.

Fig. 3. *Surface alterations produced by abusive machining.*

surface of high-strength steels is extremely detrimental to fatigue strength and stress corrosion susceptibility.

When abusive drilling was done on aged 18-percent nickel maraging steel, 52 Rc, an overaged resolutioned layer 0.001 inch deep was produced at the surface. Hardness of the layer was 37 Rc.

Abusive milling of Ti-6A1-4V produced an overheated surface layer about 0.0015 inch deep and 12 points softer than the base metal. Abusive machining can also produce cracks, laps and tears or crevice-like defects.

Nonconventional Machining Processes

Electrical discharge machining (EDM) tends to produce a surface which contains a layer of recast spattered metal. This metal is usually hard and porous and in many cases contains cracks, Fig. 3, which extend into the base metal. Below the spattered and recast metal it is possible to have the same surface alterations that occur in abusive machining. Other thermal processes such as electron beam and laser machining tend to produce the same types of surface alterations.

Electrochemical machining (ECM)

is capable of producing a surface essentially free of metallurgical surface layer alterations. However, when ECM goes out of control selective etching or intergranular attack can occur and surface roughness is promoted. A short circuit between electrode and work can cause extreme overheating and intergranular cracks.

ECM also has a tendency to produce a soft surface layer. Surface softening of 0.001 to 0.002 inch deep can result in electropolishing and chemical milling.

Residual Stress and Distortion

The machining process imparts stresses in the surface layer and these have been found to strongly influence distortion. In grinding, the residual stresses tend to be tensile under abusive conditions. By using gentle grinding conditions these stresses can be reduced in magnitude and may even become compressive.

In milling, the residual stresses tend to be compressive. The magnitude of the residual stresses and the resulting distortion are also functions of the material being machined.

Effect on Mechanical Properties

The mechanical property most sensitive to machining is high-cycle fatigue strength. Extensive investigations on high-strength steels have revealed that abusive grinding of 4340 steel at 50 Rc can reduce its endurance limit by 35 percent with respect to low stress or gentle grinding. When abusive grinding there is a tendency to form patches of untempered martensite (UTM) or overtempered martensite (OTM) on the surface. Very high reductions in endurance limit are also obtained by abusive grinding of nickel base alloys.

In end milling operations, when using the side of the cutter the abusive condition (primarily cutter dulling) tends to significantly reduce fatigue strength. However, when milling with the end of the cutter there is little difference between gentle and abusive conditions.

Electrical discharge machining produces a marked decrease in endurance limit when compared to low-stress grinding. There was little difference in fatigue properties of roughing or finishing EDM conditions.

Electrochemical machining also causes a decrease in fatigue strength, but not as great as that caused by EDM.

Stress corrosion susceptibility of high-strength steels has been found to be dependent on the presence of untempered or overtempered martensite. Testing for stress corrosion resistance is difficult as failures by this phenomenon usually occur over a period of months or years. The presence of UTM or OTM, especially in drilled or reamed holes, has been found to be one of the major causes of delayed failure on high-strength steels.

Reliability Improvement

It is apparent that to maintain or

improve the reliability of high-strength hardware it is first necessary to have a knowledge of the effects of surface integrity on the engineering properties of the alloys being used.

Many companies are controlling machining conditions by adding process specifications to metal removal operations. This is particularly important when machining high-strength steels or when employing critical operations such as EDM and ECM.

Another method of insuring high-quality surface integrity is shot peening which yields a cold-worked compressive stress layer. Such a layer generally improves fatigue strength and stress corrosion properties.

It is also important to provide quality control by inspection processes on machined components. Unfortunately, there is a limited number of practical nondestructive testing techniques available.

There is also a need for more thorough identification of surface topography—it is necessary to determine roughness over the entire surface. In structural applications the nature of the troughs on the surface is most important, while in bearing applications the nature of the crests on the surface is more significant.

Some work has been done correlating surface roughness with bearing applications. However, little work has been done to determine the relation between surface roughness per se to fatigue properties and stress corrosion susceptibility of materials.

Finally, there is evidence that machining operations and resulting surface layer conditions affect crack initiation and crack propagation and, hence, fracture toughness of material. ●●●

(This article is based on a paper presented by the author at the 18th National SAMPE Symposium held in Los Angeles.)

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