CAUTION: Surfaces may be hazardous

The performance being demanded of modern automotive and aerospace devices calls for parts with higher reliability. The answer often lies in surface integrity, an important dimension in metal working, which doesn't come cheap. This article explains the "why" and "how" of sound surfaces, and ways to get them at minimum cost.

MACHINING and grinding cause surface changes that must be reckoned with in the design and manufacture of critical automotive and aerospace components. Before long we will have planes carrying 300 to 500 people at supersonic and hypersonic speeds—under structural stresses never before dreamed of. And the automotive industry is continually striving for greater safety and reliability in the products it manufactures.

Cutting manufacturing costs is important to everyone, but must take second place when human life is involved—as it is in the products of the transportation industries.

Some claim countries like England, Germany and Russia are ahead of the US in many branches of engineering research. This is debatable; but in the field of surface integrity, the US has taken a leading role.

Surface integrity
This rather new term means the unimpaired or enhanced surface condition developed by controlled manufacturing practices. Practically, we have surface integrity whenever the surface of a part meets the demands of the stress-system in which it must operate.

Engineers have been aware for many years that the mechanical traits and service life of materials often depend on their surface characteristics rather than their bulk properties. For example, the impairing of hardened steels by grinding burn, and the beneficial effects of shot peening, tumbling and stress-relief heat treating have been recognized for a long time.

Industry has always stressed faster material removal to increase production and reduce costs. Just as casting, forging and weldment producers have long neglected the machinability of their products, few machinists ever think about the traits of the surface layer they develop during machining or grinding.

Manufacturers have not completely ignored surface integrity:

1. Experiment in progress is part of a study of the effect of milling on surface integrity. Best results were obtained with sharp tools—keeping flank wear under 0.008".
2. Drilling research shows that holes in highly stressed parts should have a surface free of tears, laps and untempered martensite.

3. Research conducted at the Metcut laboratory proves that the low-stress grinding technique promotes surface integrity.

4. Surface-ground 4340 steel has a much higher endurance limit when low-stress ground.
They set up practices to avoid grinding damage, distortion and residual stress. Also a lot of good work has gone into surface finish, including setting up finish standards for machining and grinding. Today, however, the way manufacturing processes affect the microstructure, hardness, residual stress and even the chemistry of the surfaces of components has become critical.

To get surface integrity, industry must adopt new material-removal practices. And do so carefully, knowing that surface integrity is seldom cheap: It usually entails lower production rates and higher costs.

We need more research work on fatigue and stress corrosion to answer many questions about the way processes such as milling, Figure 1, drilling, Figure 2, and EDM and ECM affect service performance. And we must use what we already know about surface integrity. For example, EDM lowers fatigue strength drastically, and many ECM surfaces have lower fatigue strength than polished surfaces. Low-stress grinding can reduce distortion and residual stress as well as minimize the chance of developing brittle or cracked layers of martensite in steels.

**High-speed/high-feed grinding**

Recently, certain abrasive-industry papers and reports have recommended high feeds and high wheel and work speeds to improve grinding efficiency and surface integrity. Because these high speeds and feeds increase output, many manufacturers may use them where they don't apply.

For many years, Metcut Research Associates Inc. has been working to find ways to minimize distortion by controlling residual stresses and to develop surface integrity by avoiding surface damage. When working on high-performance parts, a lot of time, material and money can be saved by observing the results of this research.

### Table: Grinding Conditions for Steels and For Nickel-Base High-Temperature Alloys

<table>
<thead>
<tr>
<th>Surface Grinding</th>
<th>Typical Conventional</th>
<th>Typical Low Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wheel speed</strong></td>
<td>A46K8V</td>
<td>A46H8V</td>
</tr>
<tr>
<td>5500 to 6500 fpm</td>
<td>2500 to 3000 fpm</td>
<td></td>
</tr>
<tr>
<td><strong>Down feed</strong></td>
<td>0.001&quot; to 0.003&quot;</td>
<td>0.0002&quot; to 0.003&quot;</td>
</tr>
<tr>
<td><strong>Table speed</strong></td>
<td>20 to 100 fpm</td>
<td>20 to 100 fpm</td>
</tr>
<tr>
<td><strong>Cross feed</strong></td>
<td>0.050&quot; to 0.250&quot;/pass</td>
<td>0.040&quot; to 0.250&quot;/pass</td>
</tr>
<tr>
<td><strong>Grinding fluid</strong></td>
<td>Water base, soluble oil or chemical</td>
<td>Highly sulfurized oil</td>
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<table>
<thead>
<tr>
<th>Cylindrical Grinding</th>
<th>Typical Conventional</th>
<th>Typical Low Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wheel speed</strong></td>
<td>A46K8V</td>
<td>A6016V</td>
</tr>
<tr>
<td>5500 to 6500 fpm</td>
<td>2500 to 3000 fpm</td>
<td></td>
</tr>
<tr>
<td><strong>Infeed</strong></td>
<td>0.0005&quot; to 0.002&quot;</td>
<td>0.0002&quot; to 0.002&quot;</td>
</tr>
<tr>
<td><strong>Work speed</strong></td>
<td>70 to 100 fpm</td>
<td>20 to 100 fpm</td>
</tr>
<tr>
<td><strong>Grinding fluid</strong></td>
<td>Water base, soluble oil or chemical</td>
<td>Highly sulfurized oil</td>
</tr>
</tbody>
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**Research results**

At a time when industry has serious surface-integrity commitments, there is a lack of good hard data, particularly on critical traits such as fatigue and stress corrosion. Thus, Metcut, with the help of many contractors, has been setting up general guides, such as the following, to help industry.

1) Conventional grinding practices do not promote surface integrity on highly sensitive alloys such as IN-100, 713C, MAR-M509, beryllium, tungsten, and columbium alloys. And they are not recommended for high-service-stressed sensitive alloys such as high-strength steels 4340 at 40 to 56 Rc, D6ac at 50 to 56 Rc, maraging steels and HP 9-4-45; nor for high-temperature nickel and cobalt-base alloys (wrought) such as Rene 41, Udiment 700, Waspaloy, Inconel 718 and L-605; titanium alloys such as 6Al-4V, 5Al-215 Sn and 6Al-2Sn-4Zr-2Mo; and molybdenum alloys such as TZM and Mo-0.5Ti. It should be noted also that hand grinding lacks the control needed...
for surface integrity on sensitive alloys.

2) Low-stress grinding minimizes distortion in fragile parts and reduces the chance of extensively altering their surfaces.

3) Low-stress grinding experiments, Figure 3, show that it is very important to use soft grinding wheels, low wheel speeds, low down feeds and chemically active fluids, as shown in the Table. The table speed in surface grinding and the work speed in cylindrical grinding have not been critical under Metcut's low-stress grinding conditions. However, some investigators recommend high work speeds in cylindrical grinding to minimize altering surface layers.

4) Failure studies show that it is never good practice to use hard grinding wheels at speeds around 6900 fpm for finishing structural hardware, nor hard wheels at conventional speeds for difficult-to-machine sensitive materials, Figure 4. Research data shows that accidental starvation of fluid or lack of operator control are much more harmful when using high-hardness wheels and conventional grinding speeds.

5) Residual stresses after grinding are symptoms of surface traits that seriously alter fatigue strength and other mechanical properties. Residual stress does not tell the whole story—studies show that surface alterations can take place in maraging steel without high residual stresses being present.

Metcut's research covers not only residual stress, but also—and more important — surface phenomena such as the production of untempered martensite (white layer), especially in steels like 4340 around 50 Rc, Figure 5.

Recent studies disclose overtempered martensite next to the more noticeable white layers of untempered martensite. Major inspection methods involve nitric-acid etching of high-strength steels for critical parts to find—and ultimately to eliminate—both of these types of martensite. Even very small amounts of either type are detrimental: Studies showed that surface layers of overtempered or untempered martensite as thin as 0.0005" to 0.001" on 4340 steel at 50 Rc reduced the endurance limit 35 percent.

6) Fatigue tests on EDM'd surfaces show that even very thin recast layers have a bad effect. Roughing or finishing EDM will drop the fatigue strength of low-stress-ground Inconel 718 from 50 ksi (thousands of pounds per square inch) to 22 ksi. The recast layer after EDM finishing is about 0.0001" to 0.0002" deep, but it is as harmful as a layer 10 times thicker. EDCG, EDCD or ECDM have also destroyed or impaired surface integrity.

7) Many modern applications require metallographic testing to find defects such as untempered and overtempered martensite, microcracks, builtup edge, plastic deformation and resolutioned austenite—as well as fatigue under service conditions, and stress-corrosion susceptibility.

8) Research shows that high-speed grinding (12,000 fpm and more) cuts costs, but at the present state of technology should not be used to promote surface integrity. High-speed grinding often causes residual stresses as high or higher than those you get with conventional grinding—along with untempered and overtempered martensite.

9) Fortunately, industry can make many critical parts economically by starting with high-speed grinding and then finishing with low-stress grinding, Figure 6, to restore surface integrity. This is possible because the damaged surface layers are usually less than 0.010" deep. However, it is a good idea to check for cracks after high-speed grinding because cracks in some materials may be chased in further during low-stress grinding.

Regardless of the cost, the demand for surface integrity is here to stay: everyone involved must find ways to satisfy the demand for it.