Isotropic Finishing of Helicopter and Turboprop Gearbox Components

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The traditional finishing techniques for engineered gearbox surfaces include but are not limited to hob shaving, gear grinding and honing. Regardless of the technique employed, a unidirectional polishing pattern is achieved as the final component surface finish. This pattern consists of parallel rows of asperities peaks that undergo fracturing and pulverization during the initial gearbox break-in period. This critical time results in high heat generation, high frictional force loading of the opposing engineered surfaces, metal chips in the lubricant and the initiation of future pitting or catastrophic metallurgical failure sites. By refining the engineered surfaces with an isotropic finishing process a final, non-directional surface finish is obtained. This isotropic finish requires no break-in, maintains cooler gearbox operational temperatures, generates no metal chips and most importantly, dramatically reduces the initiation of future pitting and/or metallurgical failure of gearbox components.

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Review of Traditional Gear Tooth Finishing Techniques

Helicopter transmission and turboprop gearbox components are typically cut from forged gear blanks by the use of traditional hob tooling. Hobbed gear teeth have an approximate final finish of 45-60 µinches.

In an effort to produce a lower µinch finish on the gear flank surface, gear teeth may be subjected to several sequential finishing operations. These operations typically include shaving, grinding, honing and diamond lapping. The final overall surface finishes achieved by each of these processes are detailed in Table 1.

Table 1
Final Surface Finishes Achieved by Various Gear Tooth Finishing Operations

Gear Tooth Shaving	35-60 µinches
Gear Tooth Grinding	18-40 µinches
Gear Tooth Honing	10-18 µinches
Gear Tooth Lapping	8 – 12 µinches

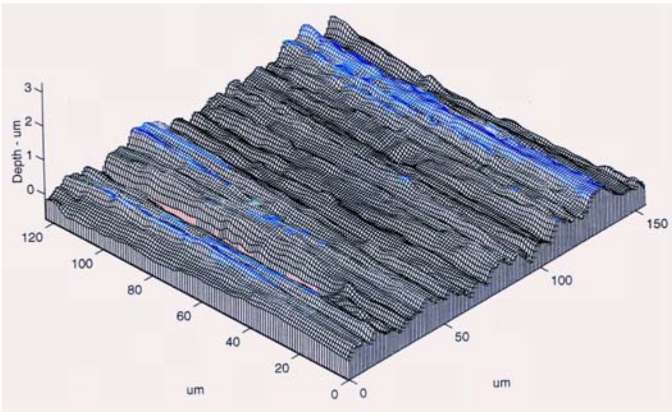
Among the traditional finishing techniques used to produce low R_a finishes, most facilities still utilize gear tooth grinding. The use of grinding wheels containing specific grades of aluminum oxide results in a specific overall finish. By sequencing successively finer grades of aluminum oxide grinding wheels, successively smoother overall final finishes can be obtained. See Table 2.

Table 2
Normal Succession of Gear Tooth Grinding Wheels

Wheel grit grade	Resultant overall surface finish
180 grit wheel	20-25 µinches
220 grit wheel	18-20 µinches
240 grit wheel	15-18 µinches
300 grit wheel	12-15 µinches

Photo 1; (below)
This photo is a close-up view of a bevel gear showing grind line patterns left in the flanks of the gear teeth following a gear grinding operation.

Figure 1; (below)
Shows a 3-dimensional view of the topography of a gear tooth that has been refined (R_a = 35 µinches) using a traditional gear grinding technique. Note the successive rows of resultant asperities corresponding to the directional pattern of the gear grinding operation.



In a gear tooth honing operation, an abrasive hone in a conformational form is rolled across the gear flank in a crossed axis pattern. Since the hone contains abrasive particles, it imparts a mechanically smoother finish to the gear flank corresponding to the size of the abrasive used to prepare the honing tool. The traditional honing operation is a wet process. An appropriate fluid is used as a lubricant and a coolant. A moderate flow rate is applied to flush away the resultant honing swarf.

Diamond lapping requires components such as transmission rings and pinions to be mated then run to break-in the components prior to final assembly. Essentially, the break-in phase for new components is accomplished at the manufacturing facility rather than in the customer's gearbox.

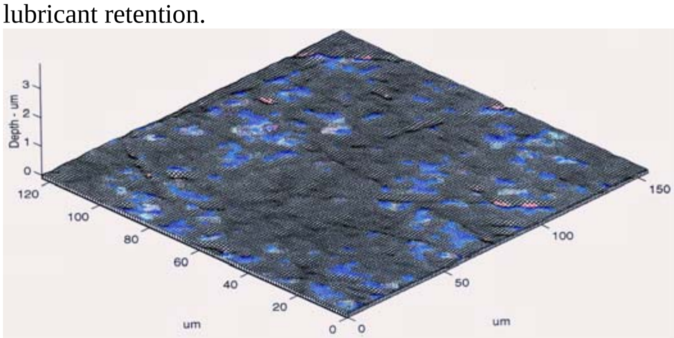
During diamond lapping the only asperities that are removed are those that are abraded at the contact points of the engaged teeth. A disadvantage to the diamond lapping technique is that lapped components must remain as matched pairs through subsequent handling operations and then final assembly. This adds a complexity to the manufacturing operation that would be better eliminated if the components could be refined in bulk then randomly combined during final assembly.

Regardless of the traditional technique used to produce the final surface finish, the overall intent of any of these finishing procedures is identical, to produce a consistently lower R_a finish on the gear tooth, than is generated during the initial gear hobbing operation.

Generating the Isotropic Finish

According to several published articles[3,8,12] metal contact surfaces, refined with chemically accelerated vibratory finishing techniques[5,6] have a superior final finish. This is due to the asperities having been chemically refined and not mechanically abraded from the surface of the engineered component.

Figure 2; (below)
Shows a 3-dimensional view of an isotropically produced surface finish (R_a = 1.5 μinches) generated by the techniques as described in[5,6,7]. Note the elimination of all asperities has improved the topography of the final gear tooth surface. The remaining low areas provide sufficient recesses for good lubricant retention.

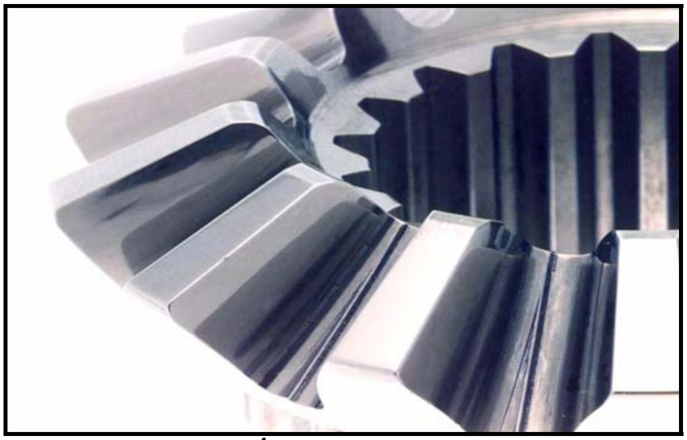


According to the techniques described by[5,6,7] asperity refinement occurs in a chemically accelerated vibratory finishing process. The gears to be refined are placed into a vibratory bowl containing a high-density, non-abrasive media[6]. The process involves two steps.

The initial step is the refinement process, wherein a chemical interaction takes place on the surface of the part[7]. A thin (1 micron) film is formed on the part surface that is soft by nature. Through the interaction of the media in the vibratory system, the "film" is physically removed from the "asperities" of the part[7]. Since the "valleys" are recessed and untouched by the media, the film remains untouched and the valleys are unaffected[7]. The chemical "film" then reforms only at the surfaces interacting with the vibratory media and the process repeats itself[7]. As a function of time, the "asperities" are removed, leaving only the valleys, thereby, generating the improved micro-finish[7].

The second step is referred to as the burnish process. After the required micro-finish is achieved, a mild alkaline mixture is introduced[7]. After a relatively short period, a mirror-like polished finish is produced[7]. Additionally, this step removes any residual film remaining from the initial refinement step. Cost savings are realized through the ability to process parts in mass, thereby, producing a superior isotropic finish at per piece costs lower than conventional machining/grinding operations.

Photo 2: (below)
Shows a chemically accelerated vibratory produced isotropically finished bevel gear (R_a = 1.5 μinches) with all asperities removed.



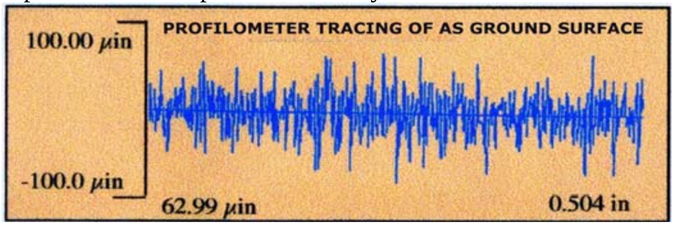
Analysis work[4] has shown that the process chemistries used in this technique produce no metallurgical degradations such as hydrogen embrittlement. This technique is a proven robust production process and can maintain gear tooth accuracy within an AGMA 14 quality number.

Benefits of the Isotropic Finish

Improved R_{sk}

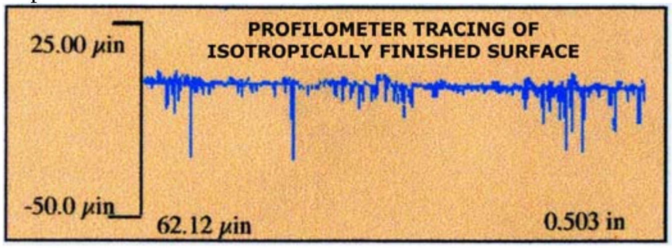
Some authors[12] refer to the resultant surface as a *No Run-In* surface. An asperity free, final surface is critical to extended gear tooth performance as is noted in [3,8,12] since the R_{sk} of the engineered surface has been improved. The skewness, i.e. R_{sk}, is a measurement of the asymmetry of the surface profile about the mean surface position. A positive skewness indicates that the most distant lying points on a surface profile are proportionately above the mean surface. A negative skewness indicates the most distant lying points are proportionately below the mean surface.

Figure 3; (below)
Shows a profilometer tracing of an as ground engineered surface with an R_a =18.94 µinches and an R_{sk}= -0.0949. Note: asperities extend upward and valleys extend downward.



Examining Figure 3, shows the initial surface has an R_{sk} near zero. There is an approximately equal distribution of asperities above and below the mean surface of the part.

Figure 4; (below)
Shows a profilometer tracing of an istropically finished surface with an R_a = 5.77 µinches and an R_{sk}= -3.0968. Note: no asperities remain above the mean part level. Since only recessed valleys remain the R_{sk} skew has been dramatically improved to a -3.0968.



By isotropically removing asperities from tooth surfaces, the R_{sk} is approximately –3 showing that the asperities were refined. This is important because all loading on this surface was previously carried by only a few of the highest asperities on the ground surface. The isotropic surface produced by the chemically accelerated vibratory finishing technique generated an asperity free surface, which effectively disperses the load across a wider area, thereby, reducing stress in any one location.

This phenomenon was clearly demonstrated in a 1994 evaluation[12] on roller bearing contact surfaces. The evaluation[12] graphed a 2.5 to 1 reduction in Hertzian stress associated with the asperities found on a traditional ground bearing surface when compared to an identical bearing surface that had been isotropically refined. Measured[12] Hertzian stress levels at surface contact asperities were found to be as high as 1.12 GPa. The authors[12] defined a 0.93 GPa Hertzian stress upper limit to asperities prior to plastic deformation. Measured[12] Hertzian stress levels for identical, isotropically refined bearings were a uniform, 0.45 Gpa.

Reduced Wear and Contact Fatigue Pitting

As discussed previously, traditional shaving, grinding, honing, and lapping techniques do not eliminate asperities; rather, they replace them with more rows of shorter asperties. Parts with this type of overall starting condition, when placed into operation for the first time, undergo a break-in period as noted by[3,8,12]. During break-in and during the normal operation of gears, asperities undergo intense plastic deformation[12], wear, and contact fatigue. Gears that undergo this type of operation experience certain surface degradation problems:

1. Snapping off of asperities results in the formation of a pit or hole at the former interface of the asperity base and the gear tooth surface.

2. A snapped off asperity becomes metal debris and is carried through the gearbox where it is interspersed between engaged gear teeth. As the asperity debris is pulverized, it generates further surface damage in the form of pits and gouges on the surface of gear teeth with which it has been interspersed.

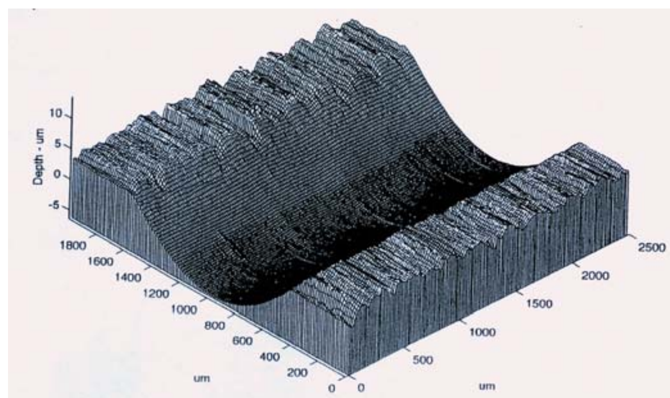
Photo #3; (below)
Shows gear tooth spalling caused by surface pit propagation. The gear shown was finished using traditional gear grinding techniques. Asperity wear during the gear break-in phase produced pits, which coalesced into irregular craters over a significant area of the gear tooth.

By preventing the generation of contact fatigue initiation sites, gear tooth durability is dramatically improved. Recent testing[2,9] has shown that isotropically finished discs resist scuffing damage at loading levels two to three times greater than traditionally ground discs.

Ring and block evaluation work[8] has shown a 22 to 1 decrease in the amount of metal wear as a direct result of the application of an isotropic finish. In this evaluation[8] sets of blocks were processed to generate a traditional ground surface and an isotropic surface. The blocks were weighed and fixtured against a ring that was rotated at 800 rpm for 6 hours. The blocks were then measured for the wear patterns produced and metal loss generated. The test showed a significantly higher volume of metal wear associated with the traditional ground surface. See Figures 4 & 5. Asperity wear and the resultant pit generation fostered a snowballing rate of metal wear.

Additional independent work[10] confirmed minimal metal removal during gear tooth refinement to generate an isotropic finish. Measurements[10] of stock removal during the isotropic finishing process showed that a minimal stock removal; 0.00012”, was necessary to impart an isotropic finish, thereby, assisting a manufacturing operation to maintaining close machining tolerances.

Figure #4; (below)
Figure #4 shows the wear pattern produced in a ring-and-block evaluation[8] on a traditionally ground steel block.



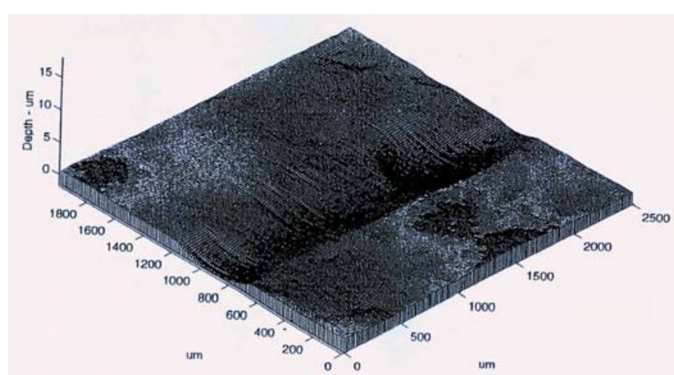


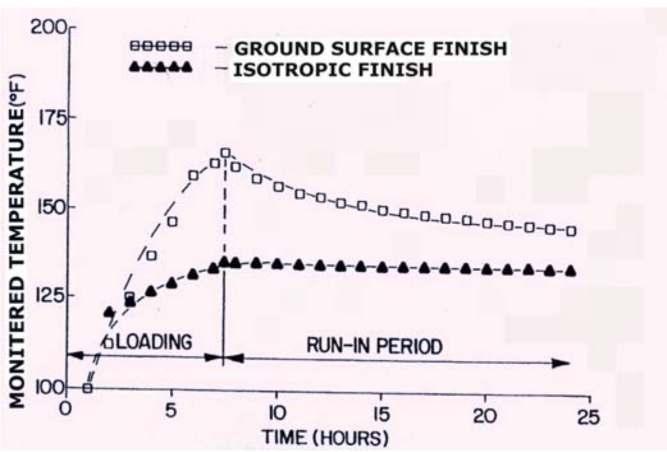
Figure #5; (above)
Figure #5 shows the wear pattern produced in a ring-and block

evaluation[8] on an isotropically finished steel block. The result of this evaluation produced 22 times less metal removal as was produced in the coupon shown in Figure #4.

Lower Operating Temperatures

Break-in periods for gear teeth and assorted engineered surfaces can easily be monitored by the temperature spike generated during the break-in procedure[3,8,11,12]. See Graph #1. Isotropically finished components require no break-in period since the starting surface is already smooth, therefore, there is no temperature spike. See Graph #1. Work done by[1,3,8,11,12] additionally demonstrates a significant reduction in continual operational temperature for isotropically finished components. See Graph #1.

Graph #1; (below)
Shows the traditional break-in temperature curve with a temperature spike for a ground surface finish versus an isotropically finished surface, which shows no corresponding temperature spike[8].



Examination of this graph shows that isotropically finished components have a gradual rise to a plateau operating temperature of 133ºF. Traditionally ground components have a temperature spike at 165ºF prior to equilibrating at a consistent operational temperature of 150ºF. In this evaluation[8], isotropically refined engineered surfaces had a durational operating temperature of 17ºF less than standard ground surfaces. This represents a 13% reduction in overall operational temperature.

Reduced Frictional Force

In a recent evaluation[2], pairs of ground and pairs of isotropically refined discs were rotated against each other in a high speed, scuffing rig. The rig allowed evaluators finite control over disc rotational frictional forces. The test evaluators could precisely increase and monitor the increased frictional forces applied to the discs until engineered surface failure; (i.e. scuffing) occurred. Additionally the rig's oil sump was equipped with a thermocouple that allowed evaluators to monitor the operating temperature of the disc sump environment[2].

The evaluation[2] showed that during high speed rotational testing; designed to simulate the sliding speeds considered typical of an aerospace gearbox - 26 m/s, traditionally ground discs failed at a force loading of 1,850 N whereas isotropically finished discs failed at a force loading of 4,150 N. This represents a 2.25 to 1 increase in disc durability. Simultaneously, the measured frictional force on the discs[2] showed that the traditionally ground discs had risen to 54.2 N as opposed to 46.5 N for the isotropically refined discs. This represents an approximate 16% reduction in the frictional force between the discs.

Monitored[2] temperature in the rig was 240ºC for traditionally ground discs and 201ºC for isotropically finished discs. This represents, a 16% reduction in oil sump temperature for the rig.

Similar testing[1] was conducted on traditionally ground and isotropically refined gears. The result of this testing was nearly identical to the disc evaluation[2] discussed above. When both gear types were tested at identical rotational speeds of 5,000 rpm, the authors[1] reported a 30% reduction in frictional torque as a result of isotropic finishing when compared to traditional ground gears. The authors[1] also noted a 10.5% reduction in the operational temperature of the rig's oil sump.

Benefits to Helicopter and Turboprop Gearbox Components

Improved R_{sk} means that components with an isotropic finish produced by the chemically accelerated vibratory process

will exceed the current engineering demands required of traditionally finished components. This suggests the possibility of using smaller components in the gearbox to safely operate at higher power densities. Smaller components mean less mass and, therefore, less weight to be lifted. Since the mass of weight to be lifted can be reduced, payload efficiency can be increased.

Lower operational temperatures mean cooler helicopter and turboprop gearboxes. Since heat is a horsepower thief, maintaining a cooler gearbox is an effective way of creating a power increase. In the gear evaluation discussed previously[1], the authors note that "although the overall gain in efficiency of power transmission of the gears as a result of these improvements are small, the reduction in total losses, if realized in high-power

reduction gears for an aircraft engine geared–fan drive, for example, could be of significant benefit in terms of the reduced cost, weight and aerodynamic penalty of cooling equipment."[1] This is an incredible benefit in the potential reduction in weight caused by eliminating or greatly downsizing lubricant cooling units aboard an aircraft and can be effectively multiplied across aircraft with multiple engines and gearboxes.

Reduction in engineered surface Hertzian contact stresses[12] reduces plastic deformation of the surface[12] asperities, thereby reducing wear and contact fatigue pitting. Since failures are exacerbated by the presence of an initiation site, eliminating these sites will foster greater component durability[2,9] and dramatically reduce replacement of gearbox components[8]. Greater gearbox durability can be directly related to lower maintenance costs and lower downtime for the aircraft.

Generating an isotropic finish on gearbox components will reduce the frictional torque required to rotate the components[1] thereby generating greater horsepower and fuel economy. Both are significant advantages to increasing payload efficiency of the aircraft.

Conclusion

In general, if two reciprocal engineered surfaces operate by sliding, rolling, meshing or pushing against each other, component performance and durability for the pair will be significantly enhanced by generating an isotropic final finish on the surfaces. Since the isotropic finish is applied with a chemically accelerated vibratory technique the surface improvement can be generated quickly and cost efficiently in a mass production method. Benefits of isotropic surface finishes have been noted as:

1. Improved R_{sk} between the reciprocal surfaces.
2. Reduced operational temperatures for reciprocal components and lubricant.
3. Reduction in the frictional force between reciprocal components.
4. Reduction of the torque required to rotate finished components.
5. Reduction of metal wear on reciprocal components.
6. Increase in gear tooth resistance to contact fatigue pitting.

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