Laser Peening Achieves Production Milestones

Laser peening continues to gain momentum as a tool for designers of critical components and for engineers looking to extend the useful life of highly stressed metal parts. This culminated in August with the issue of a new National Standard Specification for Laser Peening (AMS2546) by Aerospace Branch (AMS Committee B) of the SAE. The specification covers the requirements for computer controlled laser peening of metal part surfaces to induce residual compressive stresses at and beneath the surface and is available to the general public at the SAE website (www.sae.org).

Metal Improvement Company’s laser peening process utilizes a Lawrence Livermore National Laboratory (LLNL) designed Neodymium: glass slab laser that generates one million psi pressure pulses on the surface of metal components. The repeated pressure pulses create shockwaves that travel through the metal and impart a layer of beneficial compressive stress to the surface that is four times deeper than that attainable from conventional metal peening treatments. This compressive stress below the surface increases the component’s resistance to failure mechanisms such as fatigue, fretting fatigue and stress corrosion, which translates to increased component life and reduced maintenance costs. To see a demonstration of laser peening, go to www.metalimprovement.com/laserpeen.htm.

Metal Improvement Company (MIC) has achieved a series of other laser peening milestones in the past few years that reinforce the use of this technology as a production process:

**JAA Approval**

The Joint Aviation Authorities (JAA) awarded JAR-145 repair station approval to the MIC laser peening facility in Livermore, CA (repair station number JAA.5573). This facility commenced operations in May of 2002 to provide laser peening services on Rolls Royce Trent 800 fan blades. The MIC Livermore facility is also an approved Federal Aviation Administration repair station (MPKR633X) for specialized laser peening services.

**New UK Facility**

MIC opened its first European-based laser peening production facility in August of 2003 in Earby, Lancashire, U.K. The state-of-the-art production facility is currently providing the laser peening technology on various model turbine engine fan blade and disk components to extend their allowable time between overhaul. The facility operates two laser peening systems and is approved to ISO 9001:2000.

**10,000 Fan Blades Laser Peened**

The MIC Livermore and Earby laser peening facilities have achieved a combined milestone of laser peening over 10,000 Rolls Royce Trent fan blades. MIC has laser peened the fan blades to increase the interval between required service inspections.

**Mobile Laser Peening System Under Construction**

MIC is in the process of building a mobile laser peening system with the capability to be transferred anywhere in the world, which will bring the inherent benefits of the technology to new potential users and expand the possibilities for its use in new applications. Anticipated usage will be on large structural components subject to fatigue or stress corrosion in the aerospace, oil & gas and nuclear power industries.

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Enhancement Of Fatigue Performance Of Powdered Metal Using Shot Peening Residual Stress

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Abstract

The primary benefit of powdered metal (PM) components is reduced cost of manufacturing making PM an obvious choice for high volume applications. The perception that PM components are only limited to lower load applications has been changing with developments in higher density PM technology and advanced manufacturing techniques such as powder forging, isostatic pressing, conventional compaction, surface densification and activated sintering.

This paper will focus on fatigue strength improvements of PM components from recent innovations in PM technology combined with the established technology of shot peening. Fatigue performance and its correlation to residual stress will be discussed using several case studies on typical automotive components.

Introduction

Increasing the load carrying capacity of dynamically loaded components in automotive applications has been an ongoing activity for several decades. As the ability to carry load is improved, automotive performance can be enhanced along with potential reductions in weight. Powdered metal has been a suitable manufacturing process for the automotive industry due to its ability to produce large numbers of “near net” shape components in relatively few manufacturing steps. The continued acceptance of PM is shown in the following statistics. The bullets list the average weight of PM per automobile, by far the largest market for PM.

- 2002: 39 lbs/vehicle
- 2003: 40 lbs/vehicle
- 2004: 41.5 lbs/vehicle

These statistics demonstrates a 2.6% growth from 2002-2003 and an estimated growth of 3.8% for 2003-2004 [1].

Many other manufacturing processes (castings, forgings, machining of bar stock, etc…) have difficulty competing with the “die forming” concept of PM on the basis of cost. However, PM has traditionally not been considered for the most demanding applications due to limitations in strength and durability. This performance gap has been narrowing for years with improvements in PM technology, some of which will be discussed in this paper.

Shot peening is a cold working process that has been used effectively to enhance the fatigue strength of metal components. Shot peening received its initial acceptance in the aerospace industry before being implemented in all industries that require maximum fatigue properties of stress-sensitive components. The benefit of shot peening comes from its ability to modify residual stresses in the near-surface region of a component where most fatigue failures initiate. Shot peening produces a high magnitude residual compressive stress at the surface that works to offset initiation and propagation of fatigue cracking.

The combination of shot peening and advancing PM technology promises to offer the design engineer both reduced cost over other manufacturing processes and higher performance than previous generations of PM technology. This paper will present a brief overview of developing PM technology, an overview of shot peening theory and a number of case histories showing the benefit of combining the technologies.

Powder Metal Technology

The most important variable in growing the usage of PM in stress-sensitive applications is density. Variations in alloying content and heat treatment have contributed to PM’s advancement but are not believed to be the limiting factor to further advancements. A secondary benefit of applying PM is very uniform material response. Since the final component consists of many small particles, each of which are considered a micro-ingot, there is very little tendency for alloy segregation as with other processes such as casting. When the particles are properly mixed, a very homogenous final product is produced that should result in very consistent response to heat treating, machining and subsequent finishing operations.

“Near-fully dense” PM properties are considered less than 1% residual porosity. As further density improvements are achieved, the designer can expect to take advantage of PM’s cost savings by utilizing it in applications that were previously out of PM’s capabilities. Two technologies that will be discussed are Isostatic Pressing and Powder Forging.

Isostatic Pressing - This method of compaction is accomplished in a pressurized fluid such as water, gas or oil. The powder is encapsulated in a flexible container, commonly called a “can”, that allows forming into a multitude of near-net shapes.

A variation of this technology is Hot Isostatic Pressing. This is performed in an inert gas atmosphere (most commonly argon, nitrogen, or helium) inside a pressurized environment. Common pressures are 15,000 psi (104 MPa). Some companies claim to achieve densities of 7.5 to 7.8 g/cm³; however, typical densities for this process are 7.2 to 7.4 g/cm³.

The “can” is vacuum sealed in a container that will plastically deform at elevated temperature and pressure. Pressing and sintering occur in the same operation. Once complete, the container is removed by a process such as machining or leaching. This process can also use a previously formed component of greater than 92% theoretical density to eliminate the encapsulation stage. This component is then pressed to full density.

Powder Forging - This process begins with a “green compact” which is a PM part that
has been pressed into shape at room temperature. The part is then heated to forging temperature and restruck in a forging tool until final density has been reached.

Densities of 7.82 to 7.84 g/cm³ are currently achievable with this process. Powder forged parts are considered to have essentially wrought steel properties. This process is in current usage on automotive transmission and engine components, which tend to be some of the most highly stressed on the vehicle.

Emerging PM Technologies - Because of some economic and dimensional precision issues with powder forging and hot isostatic pressing, the focus on recent PM technological advances is on enhancements to conventional compacting, surface densification and activated sintering technologies as means for achieving gear related mechanical properties that are equivalent to wrought steels [2,3].

**Shot Peening Theory & Application**

The primary reason to shot peen components is to improve metal fatigue properties. Most automotive fatigue failures are those that occur from repeated, high stress loading of a component. Each engine revolution results in horsepower being transferred from the engine to the driveline components through a series of connected, fatigue critical components. When operating stress levels are too high or the endurance life of a component is consumed, there is the potential of fatigue crack initiation that will most likely propagate until failure under the same loading conditions.

**Figure 1** is a typical “S-N” curve. This graph is not for any particular material or application; however it clearly shows the relationship between Stress and Number of life cycles. As stress (on the vertical axis) is decreased there is an exponential increase in the number of life cycles (on the horizontal axis). At some stress level, called the endurance limit, the curve flattens out such that any stress level below it can essentially be considered infinite life. For this graph, the endurance limit is approximately 50 ksi (345 MPa). Shot peening induces a high magnitude, residual compressive stress in the near surface region of metal components, the typical initiation location of a fatigue crack. In service loading the net stress experienced by a component is the summation of applied and residual stresses. The applied stresses that cause failure are usually of a tensile nature in that they stretch and pull at the surface of the material. Compressive stresses are in the opposite direction as tensile stresses. In summary, applied (tensile) stresses are reduced by shot peening (compressive) stress resulting in significant improvements in high cycle fatigue properties.

The shot peening process showers a component with thousands of spherical media at high velocity. Each individual impact stretches the surface creating a localized area of tensile yielding (Figure 2). The surface then attempts to restore itself to its original shape creating a permanent location of residual compression (Figure 3). Repeated impacts create a uniform layer of residual compression that resists fatigue crack initiation and growth. Figures 2 and 3 show exaggerated examples of surface yielding and restoration to help explain the theory of creating the residual compressive stress.

The residual compressive stress from shot peening is proportional to the strength properties of the material’s surface. For PM components this means that higher density (and higher hardness) components will produce a higher magnitude of Maximum Compressive Stress (see Figure 4) than lower density (and lower hardness) components.

**Figure 4** does not have numeric values on it however, the variables of concern are labeled. The Maximum Compressive Stress is usually 0.001-0.002” (0.03-0.05 mm) below the surface. It is proportional to the ultimate tensile strength (UTS) of the surface properties of the material. For wrought materials, the maximum compressive stress is ~ 55% of the UTS. For example, a wrought steel with a surface UTS of 200 ksi (1380 MPa) would result in a maximum compressive stress of ~ 110 ksi (758 MPa). The residual compressive stress is the
amount that the applied tensile stress from service loading is reduced.

The Depth of Compressive Layer can vary significantly depending on the material’s hardness and the shot callout parameters. In most cases, this depth is between 0.005-0.020” (0.13-0.51 mm) deep. It should be noted that the surface residual compressive stresses are balanced with subsurface residual tensile stresses. The surface compressive stress is usually less than the maximum compressive stress [4].

Presentation Of Test Data

Case Study #1: Comparison of Wrought Steel to Powdered Metal Gears - Figure 5 shows a comparison of similar geometry wrought gears (16MnCr5) and PM gears (Fe-3.5Mo, 7.5 g/cm³) both at a surface hardness of 60 HRC. The solid curves both represent unpeened conditions. The dashed curves show the improvements with shot peening.

The PM gears responded with an ~ 35% improvement in tooth root strength when shot peened versus an ~ 45% improvement with the wrought gears (when shot peened). The shot peened PM gears compare very close to the unpeened wrought gears at 10 million cycles [5].

Case Study #2: PM Test Bars with Machined Notch - Figure 6 shows the results of bending fatigue tests performed to PM test bars with a machined notch (k = 1.49). The PM alloy was Fe-2%, Cu-2.5%, Ni- with a density of 7.6 g/cm³. Figure 6 shows a comparison of the “as sintered”, “sintered and shot peened (SP)” and “sintered, carbonitrided (CN), and shot peened (SP)” results. Shot peening improved the “as sintered” condition by ~ 21%.

With CN & SP the improvement over the “as sintered” condition was ~ 73%. This was because the hardened surface not only has higher strength but is able to retain much more residual compressive stress than the “as sintered” condition for fatigue crack resistance [6].

Case Study #3: MSP4.0Mo Ally Gears - Figure 7 shows the tooth root bending fatigue results comparing a (reference) wrought gear to similar powder metal gears.

The three materials under analysis consist of:
- Variation 1: MSP4.0Mo powder metal (7.72 g/cm³)
- Variation 2: MSP4.0Mo powder metal (7.76 g/cm³)

Figure 7 demonstrates that both versions of the PM do not have the fatigue properties of the wrought steel in the unpeened condition. After shot peening, both versions of the PM exceed the unpeened wrought steel. The combination of PM and shot peening is most likely significantly less than the cost of the wrought steel without shot peening [7].

Case Study #4: Powder Forged Connecting Rods - Connecting rods require continuous improvements in the strength-weight ratio without compromising reliability. To quantify the improvement from shot peening of PM connecting rods, powder forged (Cu-2%, C-0.5%, S-0.1%) rods and additional test specimens were evaluated in fully reversed axial fatigue testing. The PM density after the forging operation was 7.82 g/cm³.

The optimal shot peening intensity was found to be 0.017”-0.020” (0.43-0.51 mm) A using a 0.023” (0.58 mm) nominal diameter (ø) shot. The maximum compressive stress achieved from this peening operation was 73 ksi (500 MPa) with a compressive layer depth of 0.014” (0.37 mm).
Fatigue Strength - ksi

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<th>Reference</th>
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Bending Fatigue Strength
@ 2 Million Cycles

The shot peened connecting rods showed a fatigue strength improvement of 27%. The shot peened test specimens showed a 55% improvement in fatigue strength. The difference is attributed to the geometric differences of the connecting rods and the “necked down” test specimens. Published literature shows a reduced scatter band of fatigue tests with shot peening when compared to unpeened specimens [8].

**Case Study #5: Crush and Surface Durability Improvements** - In addition to improvements of mechanical fatigue properties, test results on shot peened PM components have demonstrated improvements that are not traditionally experienced with wrought steels and shot peening.

The following tests on PM components have shown improvements in impact and crush properties when incorporating shot peening [9].

- Gears (impact test): Test results have shown impact strength improvements of 70%.
- Gears (drop test): Test results have shown un-peened gear teeth broke when dropped from a height of 16 inches. Similar peened gears required a height of 21 inches before breaking.
- Gears (crush test): Test results on spur gears showed an average improvement of 44% when compared to unpeened gears.
- Sprockets (crush tests): Tests showed a 23% improvement when compared to unpeened sprockets.

The following test has shown improvements in contact fatigue properties when incorporating shot peening [10].

- Gears (flank pitting): Finish ground, plasma case hardened (spur) gears were tested for tooth flank surface durability using a power recirculating test rig. The following shot peening callouts were evaluated:
  - 0.007” (0.19 mm) shot ø at 0.007” (0.19 mm) A intensity
  - 0.023” (0.58 mm) shot ø at 0.014” (0.36 mm) A intensity
  - 0.023” (0.58 mm) shot ø at 0.020” (0.52 mm) A intensity
  - 0.031” (0.78 mm) shot ø at 0.025” (0.64 mm) A intensity

All shot peening callouts resulted in improvements in pitting resistance; however, the 0.007” (0.19 mm) shot ø gave the best improvement in surface durability. It was believed that the higher shot callouts resulted in too much surface roughness thus limiting the increase in pitting resistance.

**Conclusion**

With the continued expansion of PM into dynamically loaded components, it is inevitable that performance limitations will be encountered as designers continue to push for the maximum operating conditions. This paper has presented the theory and a number of case studies to support shot peening PM components to induce residual compressive stress for enhancement of fatigue properties. It is generally believed that the addition of shot peening to PM components will have significant cost advantages over similar wrought steel components without shot peening.

**References**


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Curtiss-Wright Acquires E/M Coating Services Business In United Kingdom

Curtiss-Wright Corporation, the parent firm of Metal Improvement Company, has acquired the assets of a coatings business located in Evesham, United Kingdom.

The E/M Coating Services facility in Evesham applies a broad range of solid film lubricant (SFL) coatings that provide lubrication, corrosion resistance and enhanced operating performance for metal components. The coatings, offered under the trade names of Everlube®, Ever-Slik®, Lube-Lok®, Lubri-Bond®, Flurene® and Perma-Slik®, are applied to steel, titanium and aluminum substrates. SFL coatings are effective in a broad range of applications whenever conventional wet lubricants provide insufficient protection due to high temperatures, extreme loads, corrosion, wear, chemical corrosion and other adverse operating conditions.

The 32,000-square-foot facility applies coatings for the automotive, oil exploration, aerospace and specialty industrial markets and is ISO9001 certified. It will operate as part of the E/M Coating Services business unit of the Metal Improvement Company. Curtiss-Wright previously acquired six E/M Coating Services facilities in 2003. E/M Coating Services is the largest applicator of SFL coatings in North America.

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MIC Bensalem Facility Expands Metal Finishing Capabilities

Metal Improvement Company (MIC) has expanded the metal finishing capabilities of its Bensalem, PA facility by the addition of fluoropolymer powder and liquid coating capabilities. Combined with its capabilities for pre-treating of Aluminum components up to 38 feet long, MIC is a premier supplier of protective and decorative coatings for large aluminum components such as poles or masts.

The specific new coating capabilities include the application of a wide range of fluoropolymer coatings such as PTFE, FEP, PFA, ETFE, PVDF, Xylan® and Halar®. The facility also features the capability to apply Epoxy, Polyester, Phenolic, Nylon 11, Everlube® solid film lubricant (SFL) and architectural powder coatings. These coatings are applied in humidity/temperature controlled clean rooms and paint booths and cured in large batch ovens.

The MIC Bensalem facility, located in suburban Philadelphia, has over 200,000 square feet of processing space, and services the aerospace and other specialty industries. In addition to coatings, the facility performs a range of complementary metal finishing services including fluorescent penetrant inspection (FPI), chromic/phosphoric acid anodizing, Alodine®, grit blasting, glass beading and shot peening. Automated chemical processing tanks allow the processing of large single components, measuring up to 38 feet long by 10 feet high by 2 feet wide, or large batches of smaller parts with assured repeatability for consistent quality.

The MIC Bensalem facility holds multiple approvals from original equipment manufacturers, including Airbus, Bell Helicopter, Boeing, Bombardier, Cessna, De Havilland and Sikorsky. The National Aerospace and Defense Contractors Accreditation Program (NADCAP) has accredited the facility’s quality system and its FPI capability.

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Heat Treatment Facilities Earn NADCAP Approvals

Three Metal Improvement Company (MIC) heat treatment facilities in Wichita, KS have successfully completed their NADCAP reaccredidation audits.

The MIC facility on McLean Boulevard, which specializes in performing carburizing, carbonitriding, and neutral hardening processes, maintained its NADCAP approval for heat treatment of ferrous-based materials. The facility on West Street, which specializes in heat treatment and straightening of aluminum aerospace structural components, maintained its NADCAP approval for heat treatment of aluminum alloys. The facility on Ida Street maintained its NADCAP approval for vacuum heat treating and also specializes in induction hardening.

NADCAP (National Aerospace and Defense Contractors Association) is a globally recognized quality assessment program that is driven by leaders in the aerospace industry. NADCAP accredits special process suppliers that demonstrate the ability to integrate stringent quality system standards into operational activities. MIC’s heat treatment facility in Roselle, NJ also is NADCAP accredited.

MIC operates a network of nine heat treatment facilities located throughout the U.S.

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