PONTOGLIO VINCENZA & C. Srl

SHOT PEENING

"CONTROLLED SHOT PEENING"

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INTRODUCTION

FATIGUE

Knowledge about fatigue failure in mechanical components is relatively recent and certainly does not cover the entire range of tribological aspects.

Fatigue refers to all time-varying stresses to which a mechanical component is subjected during operation. Thus, the term fatigue encompasses various phenomena such as mechanical fatigue, thermal fatigue, pitting, fretting, scuffing, etc. It is therefore clear that discussing fatigue without any specific clarification can be rather generic.

TYPES OF FAILURE AND DEFECT NUCLEATION MECHANISM

The phenomenon that tends to unify all these tribological behaviors is the fact that the applied loads are significantly lower than the material's yield strength. Fatigue failures, in fact, occur under relatively low loads after a period of use, typically over many cycles.

As is now well known, the mechanism of fatigue failure in a mechanical component made of metallic material originates from defects within the material itself.

These defects may arise from manufacturing processes—such as potential cracks in weld seams—or from intrinsic causes within the material, such as voids, dislocations, etc.

Metallic materials are crystalline, meaning they are composed of atoms arranged in an orderly fashion. Most metallic materials are polycrystalline, i.e., they are made up of a large number of crystals or grains, each with its own internal structure.

Each grain has its own characteristics, such as orientation and mechanical properties. Material defects alter the original properties of the crystal structure. These defects primarily affect the ability of atomic planes to slide over one another, significantly increasing this capability.

According to authoritative sources such as Fuchs, the initial slippages occur in those grains whose crystal planes are aligned with the direction of maximum applied shear stress. Subsequently, more difficult slippages take place, and so on.

These slippages, which occur under both static and cyclic loads, gradually alter the surface, forming actual intrusion and extrusion bands, as illustrated in Fig.1.

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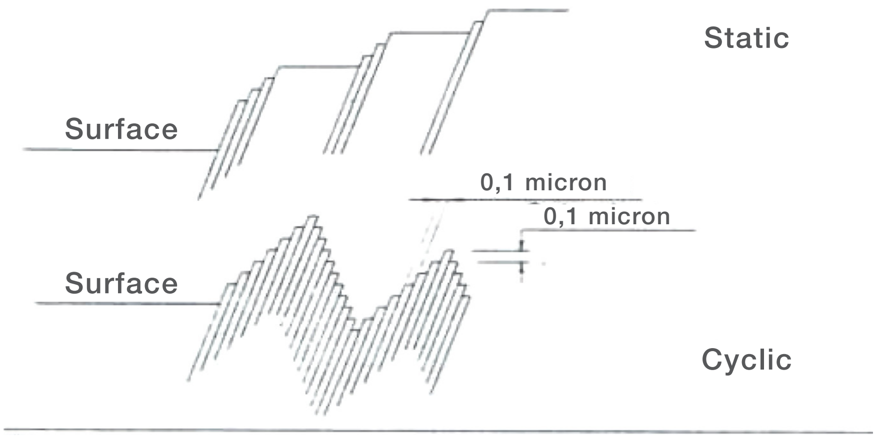
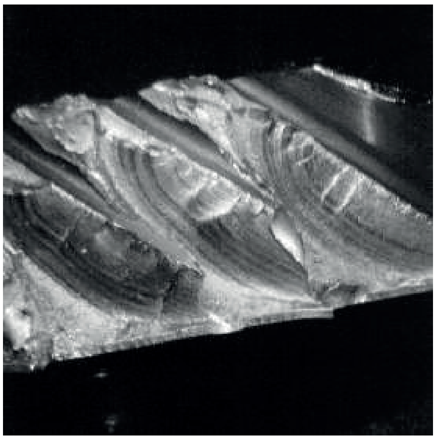


Fig.1

These bands create significant stress concentration effects. In this way, a micro-crack forms, initially governed by shear stresses. At a depth of a few grains, the crack deviates and propagates in a zigzag pattern, but tends to follow a path perpendicular to the direction of maximum normal stress. Under cyclic loading, the micro-crack initially propagates slowly, then increasingly faster. If the area is consistently subjected to tensile stress, "beach marks" can be observed—these are the striations left by the crack as it advances. The crack continues until the remaining cross-section becomes too small to withstand the external load: at that point, a sudden brittle fracture occurs. The phenomenon is extremely complex, and no unified failure theory currently exists that can fully describe the fatigue failure mechanism in a single formulation.

This highlights the insidious nature of fatigue and the importance of treatments aimed at mitigating its effects. Controlled shot peening is currently considered one of the most effective methods in this regard. In the images that follow, some typical fracture surfaces are shown.



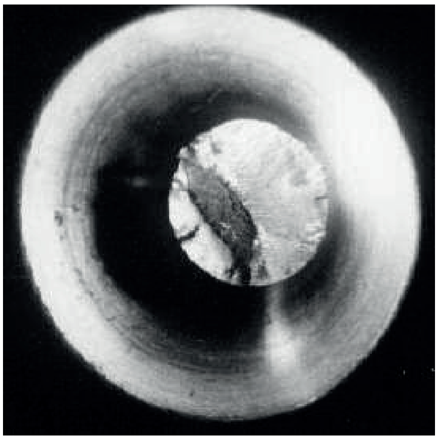


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Fig. 4 – Fatigue test specimen; uniaxial fatigue

Fig. 5 – Screw

CONTROLLED SHOT PEENING

ACHIEVABLE BENEFITS

Controlled shot peening is a treatment designed to improve the fatigue resistance of case-hardened, nitrided, or quenched and tempered parts. This treatment can reach considerable depths and is often employed to delay or eliminate failures associated with stress corrosion, fretting, pitting, and to mitigate the negative effects of surface decarburization.

In the aerospace industry, it is also used prior to electroplating processes to eliminate hydrogen embrittlement caused by coating deposition.

The strength improvements achievable through this treatment are often quite significant. These improvements depend not only on the characteristics of the peening process itself, but also on the surface condition of the component and the applied loading conditions. Table 1 shows some of the most common results obtained.

SURFACE CONDITION before shot peening	STRENGTH INCREASE fatigue limit
Smooth surfaces	10 ÷ 20%
Rough surfaces or with defects	50 ÷ 70%
Surfaces with notch effect	Notch effect eliminated

Table 1 – Achievable Strength creases

To better understand the effectiveness of the treatment, if we assume, for example, a 20% improvement in the fatigue limit as indicated in Table 1, it can be observed from the Wöhler diagram (Fig. 2) that, for high loads, lifetime improvements of 300% to 1500% can be achieved—and even greater gains can be observed for loads approaching the fatigue limit.

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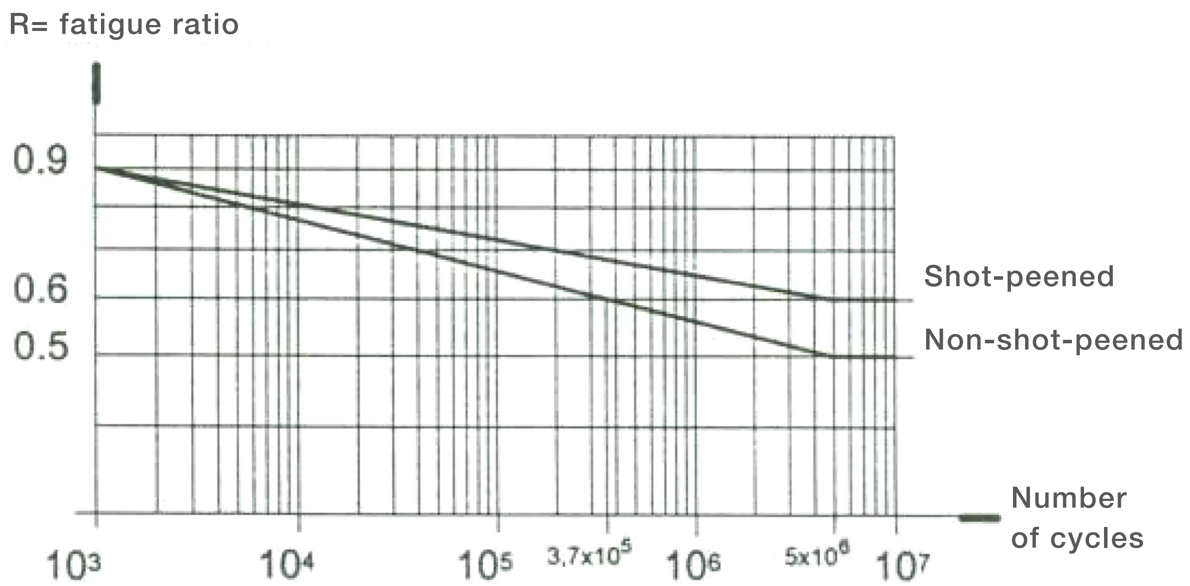

Fig. 10 – Wöhler Diagram for a Fully Reversed (Symmetrical Alternating) Load Cycle

If the applied load is below the fatigue limit, a significant increase in reliability can be achieved. This effect becomes even more pronounced in the presence of notch effects, which are very common in mechanical components. In fact, it can be emphasized that controlled shot peening is most effective in all components made critical by disadvantageous geometries, shape factors, notch effects, or the use of brittle materials. Table 2 lists the lifetime increases that can be observed on various mechanical components

COMPONENT	Fatigue Life Increase (% increase in number of cycles)
Leaf springs	600 %
Crankshafts	900 %
Connecting rods, torsion bars	1000 %
Coil springs	1400 %
Gears	1500 %

Table 2 – Lifetime Increases of Selected Mechanical Components

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It can therefore be concluded that, with regard to mechanical fatigue, the advantages of using the treatment are truly significant.

It allows for extending the service life of the component, increasing operating load levels, reducing weight and overall dimensions, using high-strength materials that are otherwise considered too sensitive to notching, and in some cases improving lubrication conditions. In certain situations, it can even help avoid costly redesigns.

THE PROCESS

Controlled shot peening is a cold mechanical treatment. It consists of striking the surface of a metal component with a stream of small shot particles projected at high speed—typically between 80 and 120 m/s.The impact of the shot on the component surface causes plastic deformation of the surface fibers; generally, this effect affects a depth of a few tenths of a millimeter. The underlying metal is not subjected to plastic deformation. The outer fibers, having been elastically stretched, tend to expand, while the material beneath the plastically deformed layer tends to restore them to their original position.The resulting balance generates a residual compressive stress in the surface plastic layer.

This leads, as previously mentioned, to a significant improvement in the fatigue life of treated components. To summarize, controlled shot peening produces the following effects on the component:

- plastic deformation of the material's surface layers
- introduction of residual compressive stresses
- work hardening of the plastic layer
- modification of surface roughness

To achieve maximum effectiveness, the process must be performed under strictly controlled and repeatable conditions—otherwise, it would be impossible to predict the condition of the components after peening.

MAIN PARAMETERS

The characteristics of the part to be shot peened often influence the selection of process parameters. The outcome of the treatment depends not only on the features of the machine and the incident shot stream, but also on the mechanical behavior of the material being peened. The machine and the shot stream are defined by a large number of parameters that must be carefully controlled during processing in order to ensure consistent and effective results.

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Below are some of the most important elements to consider for the correct application and control of the shot peening treatment::

- characteristics of the machine
- type, hardness, density, and diameter of the shot
- mechanical and geometric properties of the shot
- angle of impact
- coverage rate

The large number of independent variables has made it necessary to implement a reproducibility control system through a standardized method based on three fundamental parameters:

- type of shot (size, material, geometry, hardness)
- peening intensity
- coverage rate

The correct selection of each of these three parameters determines—on a case-by-case basis—the effectiveness of the treatment.

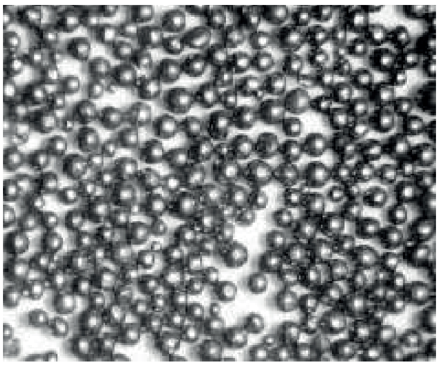
INSPECTIONS

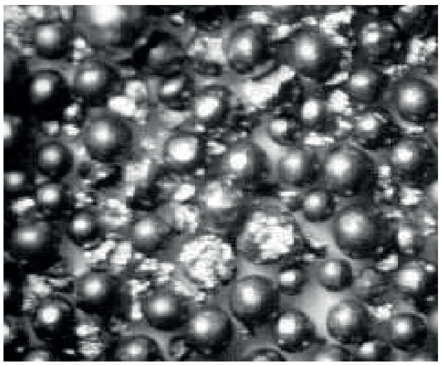
The reliability and repeatability of the treatment require a series of inspections and controls, some of which are absolutely essential and others recommended. Table 3 on page 10 lists the main ones.

SHOT CONTROL

It is immediately clear that the shape of the shot must necessarily be spherical. Non-spherical shot could damage the surface and promote crack initiation.

Therefore, it is essential to equip the shot peening machine with appropriate devices that monitor the granulometry (particle size distribution) of the shot and remove broken or deformed particles. An additional system must ensure that the shot size remains within the specified range. The images that follow show examples of shot in good condition and rejected shot sorted out by separation and calibration devices.





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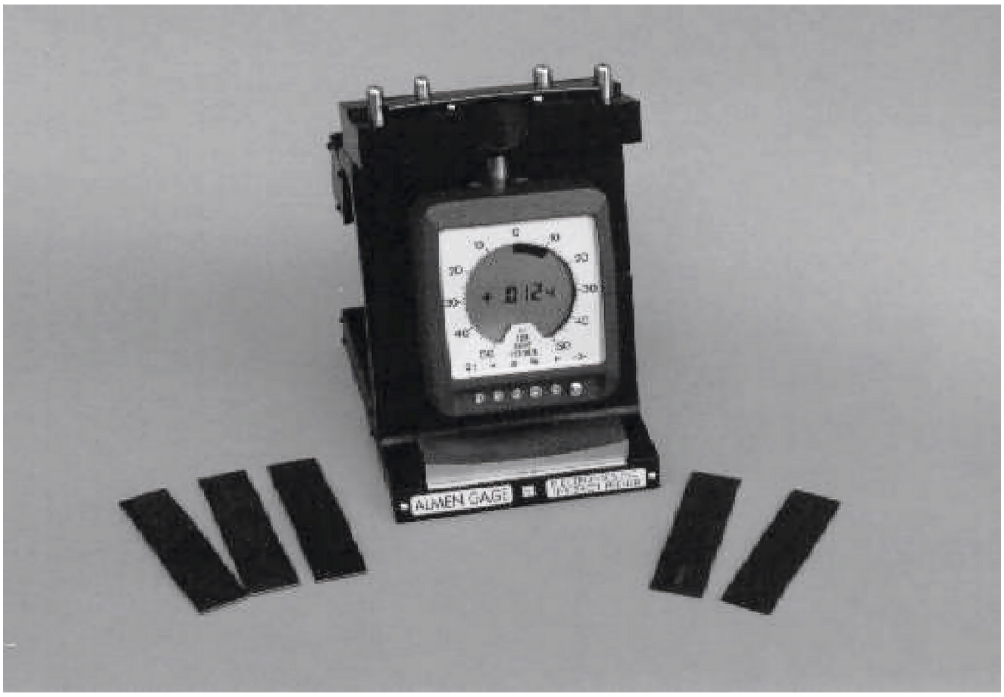
MEASUREMENT AND CONTROL OF SHOT PEENING INTENSITY

Shot peening intensity, which is measured and controlled using standardized test strips, enables the monitoring of the main parameters responsible for surface deformation of the part, and therefore ensures the correct adjustment of the machine.

The intensity is expressed in Almen grades, named after the inventor of the test. There are three available measurement scales: N, A, and C. The principle is as follows: A standard test strip of type N, A, or C is mounted on a standardized holder and subjected to shot peening. Due to the residual stresses introduced by the treatment, the strip bends into a convex shape on the peened side.

The last two digits of the arc height measurement, expressed in millimeters, represent the Almen intensity value. This measurement must, of course, be carried out using a standardized and calibrated instrument. Figure 13 shows the measurement device and the test strips.



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The three measurement scales differ based on the type of test strip used and are applied according to the following criteria:

- Almen N scale (type N strip): for low-intensity shot peening
- Almen A scale (type A strip): for medium-intensity shot peening
- Almen C scale (type C strip): for high-intensity shot peening

The N, A, and C strips differ only in thickness; the other two dimensions remain unchanged. The varying thickness of the strips makes them more or less sensitive to the effects of shot peening, allowing for readings that are compatible with the sensitivity of the instrument under all working conditions.

Shot peening intensity, as a function of exposure time to the shot stream, varies according to a curve like the one shown in Figure 14.

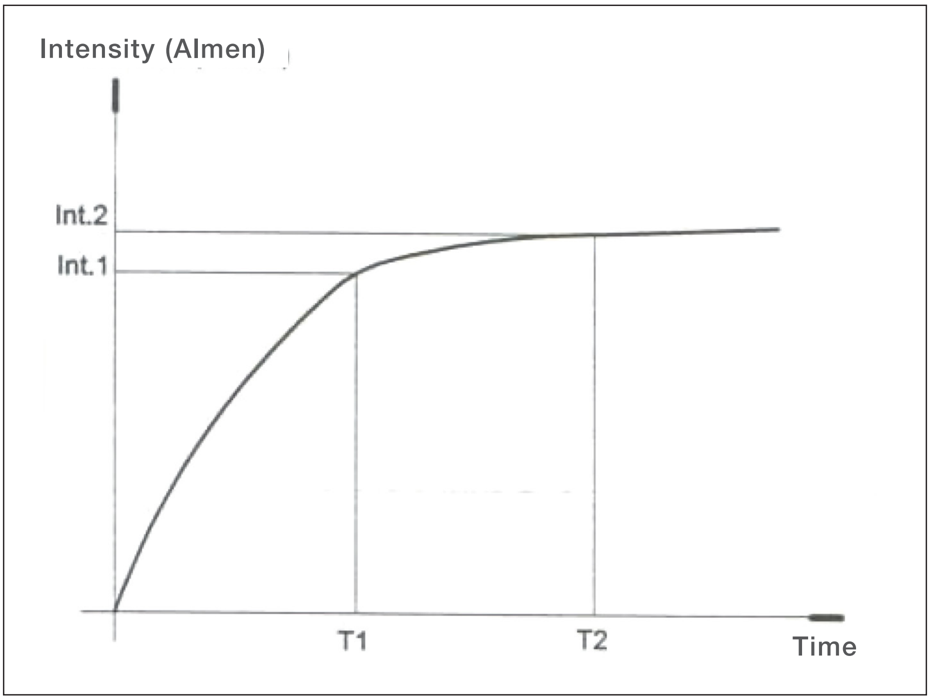

Fig. 14 – Saturation curve

At first, the test strip bends in an approximately linear manner with respect to time. The shot indentations on the surface are relatively spaced out; as time increases, the number of impacts grows, and the intensity rises, though less sharply. Eventually, the intensity-time curve shows a "knee," corresponding to a surface coverage value approaching 100%.

Shot peening intensity is defined as the intensity value for which doubling the exposure time results in no more than a 10% increase in that value.

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COVERAGE

Coverage refers to the percentage ratio between the impacted surface area and the total surface area to be treated. Control is carried out using an optical microscope and special fluorescent liquids.

INSPECTIONS		MANDATORY	RECOMMENDED
SHOT PEENING			
Incoming inspection:	Chemical analysis		X
	Particle size distribution	X	
	Hardness		X
	Shape	X	
In-process inspection:	Particle size distribution	X	
	Hardness		X
	Shape	X	
SHOT PEENING			
Almen intensity:	Saturation curve	X	
Compressed air machine:	Air pressure	X	
	Shot flow rate		X
Prototype testing		X	
Movements		X	
Times and cycles		X	
PEENED PART			
Coverage control:	Visual	X	
	Microscope	X	
	Fluorescent liquids		X
Surface roughness			X
Surface work hardening			X
Plasticized depth			X
Residual stresses			X
Fatigue simulations			X

Table 3 – Control Table

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INTRODUCTION OF RESIDUAL STRESSES

The introduction of residual stresses into the part occurs through a mechanism that combines two phenomena (Fig. 17):

- Elongation of the surface layers caused by the impact marks of the shot;

- Plastic deformation of the sub-surface layers due to Hertzian contact phenomena.

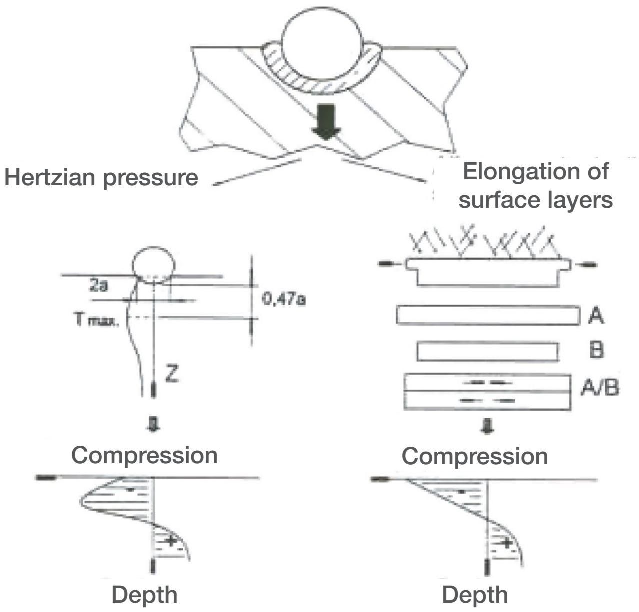

Fig. 17 – Introduction of residual stresses

The intentional predominance of one phenomenon over the other results in a residual stress distribution of the type shown in Fig. 18.

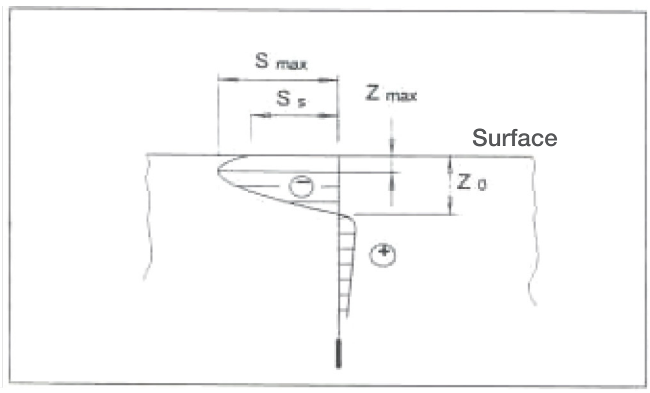

Fig. 18 – Residual Stress Profile

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The effect of the superposition of residual stresses resulting from shot peening and external loads, in the case of a component subjected to bending, is illustrated in the following figures.

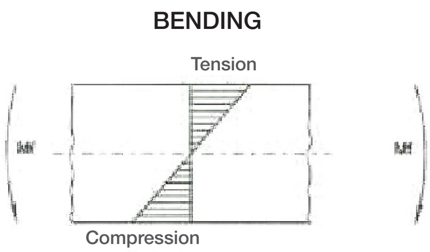

Fig. 19 – Component Subjected to Bending

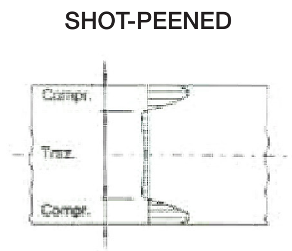

Fig. 20 – Shot-Peened Component

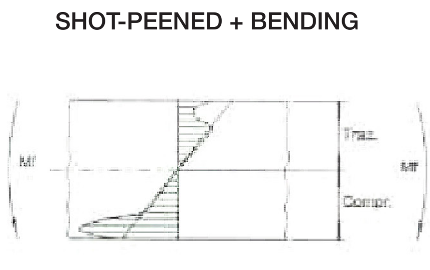

Fig. 21 – Shot-Peened Component Subjected to Bending

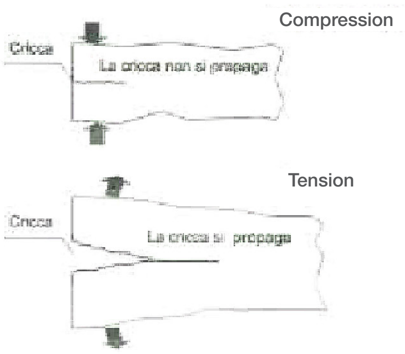

Fig. 22 – Crack Propagation

The tensile side of the component is relieved, allowing an increase in working load, while the compressive side redistributes the stresses by plastifying a depth greater than theoretical expectations.

The main advantage of introducing residual compressive stresses is the delay or complete prevention of crack propagation, as illustrated in Fig. 22.

Many years of research in this field have led to the development of sufficiently reliable numerical methods that take into account the stresses induced by shot peening in the fatigue analysis of machine components.

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WHICH PARTS TO SHOT PEEN?

The range of applications in which this treatment can deliver excellent results is truly remarkable. As already mentioned, controlled shot peening can be successfully employed in the vast majority of tribological phenomena.

Springs are an excellent example of a suitable application. In these components, the external load is almost always unidirectional, and the benefits obtained can be substantial.

Connecting rods are extremely stressed mechanical parts, and their geometry inherently leads to substantial notch effects. Scientific studies have shown that controlled shot peening is particularly effective in the presence of such stress concentrators.

Shafts, axles, and crankshaft are often peened at grooves, fillets, and other areas frequently associated with crack initiation.

Welds are always highly sensitive points in mechanical components. They are often sources of defects and residual tensile stresses. The benefits obtainable in these areas are truly impressive and are primarily attributed to three key effects

- improved resistance to pitting
- enhanced fatigue strength at the root of gear teeth
- improved lubrication conditions: the surface roughness generated by peening creates micro-reservoirs that help retain the lubricant, enabling better adhesion to the surface.

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