Shot Peening: Methods of Application of the Treatment and Induced Effects

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Article Publishing History

Article Metrics

Article Received on : 20 Dec 2022

Article Accepted on : 30 Dec 2022

Article Published : 02 Jan 2023

Plagiarism Check: Yes

Final Approval by: Dr. Satyabrata Jit

Introduction

Shot peening ranks among the most important surface treatments and with the greatest potential for development in the near future also thanks to its ductility of use, which allows its application in many industrial sectors, and to the reduced environmental impact (shot peening does not require the disposal of toxic waste) [1-4]. This treatment basically consists of bombarding the surface of a component with small spheres (or at least spheroid-shaped elements), called shots, which are launched at high speeds (ranging from about 40 m/s up to 120 m/s) using compressed air. For the treatment to be successful, it is necessary that the stresses caused in the surface fibres exceed the yield strength of the material, so that the balls are able to plastically deform the shot surface, leaving a small imprint on it. Below the surface, the innermost fibres of material try to return to their original position prior to the ball impact (to respect material continuity, two adjacent fibres must have the same length) and this induces a favourable residual stress field in the material layers close to the surface of the treated component. Shot peening therefore creates a layer of material that exhibits the typical characteristics resulting from cold working and in which residual compressive stresses are present, thus succeeding in summing up the benefits of both these effects. The residual stresses play the main role in increasing the fatigue strength and improve the behaviour of the mechanical component even in the presence of corrosion and fatigue phenomena, stress corrosion, hydrogen embrittlement, cavitation and fretting; conversely, the increased hardness due to cold working increases the resistance to intergranular corrosion and modifies the crystalline structure by closing any porosity present [5-7]. If the material is shot peened in such a way as to create, due to the impact of several spheres, numerous indentations that uniformly cover each other, a more or less deep surface layer subject to a residual compressive stress state is obtained. It is known that cracks do not nucleate and propagate in compressed areas and it is also known that fatigue and stress corrosion failures generally begin at the surface, so it is evident how shot peening can considerably increase the fatigue limit of a component and in any case increase its service life. The treatment is applied to components made of both steel and light alloys (in the aeronautical field, many aluminium components undergo peening treatment) [8-11].

Mechanical components subjected to shot peening treatment

The automotive industry was the first to adopt shot peening as an additional treatment to increase the fatigue strength of various components. Historically, the first industry to use it was the valve springs of internal combustion engines; all automobile engines have contained shot-peened valve springs for many years now. Cylindrical helical springs subjected to compression loads (torsion springs) are probably the best-known and most commonly used shot-peened components. Numerous years of experience have led to a certain amount of basic information that is a compulsory starting point for future research [12-15]. In particular, shot peening can be used advantageously both in the production of large-scale components, such as valve springs, and for individual components, such as cylinder heads for racing cars. All metal components can be shot peened; therefore, in addition to steel (the use of materials with high mechanical properties in low load cycles allows for excellent results, such as for connecting rods) also aluminium alloys, magnesium or titanium and, unlike shot peening, whose applicability is dependent on the shape of the surface, shot peening has no such constraints, being able to adapt to any type of geometry of the component to be treated (remember that it is also possible to directly shot peen the component mounted on the machine). Often the transfer of results, obtained in the laboratory with test specimens, to the industrial production cycle has revealed more problems than expected, as it is not so trivial to reproduce the geometry of the component and the stress cycles to which the component is actually subjected. The automotive industry has always tried to overcome these drawbacks by employing considerable economic and technological resources, for example by using not the test specimens, but the components themselves in experimental tests (this policy has yielded excellent results). Below is a list of some of the main components usually treated with shot peening:

– engine blocks

– connecting rods

– valve springs in internal combustion engines

– rocker arms

– compressor components

– injector nozzles in diesel engines

– suspension springs

– axle shafts

– steering arms

Piston rods

A surface with a coarse finish under compressive stress resists fatigue better than a smooth surface under tensile stress. It is generally not advantageous to achieve a good surface finish before shot peening. If this is required, the surface can be lapped or polished after shot peening so that the layer of material removed does not exceed 10 per cent of the compressed area. The critical areas (with the highest stress concentration) of connecting rods are the connecting radii close to both holes; normally, connecting rods are shot peened entirely before machining the holes. Experimental tests have shown that the peened surface protects so well that even possible scratches after the peening treatment do not cause a reduction in fatigue strength as long as they are less than a quarter of the depth of the compressed layer. Connecting rods made of various metal alloys, including sintered connecting rods, are shot peened to increase their fatigue strength. In addition, shot peening minimises the risk of breakage due to fretting on the inner surfaces of connecting rod bores. Fretting develops due to relative movement of microscopic amplitude between two metal surfaces. A thin abrasive oxide forms on the contacting surfaces, which contributes to fretting. It can result in one or more forms of damage, such as fretting corrosion, surface wear and fretting fatigue. Surface discolouration, deposited oxide layers and changes in part size are all characteristics of these forms of damage. Fretting fatigue is any type of fatigue damage that begins as a result of fretting. The major characteristic of this form of damage is a reduction in the fatigue strength of the components.

Crankshafts

The most heavily stressed area of a crankshaft is around the crankpin connection. In particular, the most stressed point is the lower side of the connecting radius; the maximum stress is reached during work cycles when the crankpin is in the top dead centre position. Generally, cracks form in the crankpin radius and propagate through the crankshaft boss (flank) to the crankpin radius, causing fatigue cracking. From an economic point of view, the reuse of large crankshafts after an overhaul is currently emphasised, which basically consists of inspecting the shafts for cracks. The shafts are then ground to a condition similar to that of newly manufactured shafts, even if the original manufacturer had not initially cold-worked the radii. These, in fact, should be cold-worked after grinding. Controlled shot peening is the best way to restore the effect of cold machining and the residual stress field induced by it. Crankshafts of all sizes, from small high-speed rotating shafts with a journal diameter of 10-20 mm to large crankshafts used in slow diesel engines with diameters up to 150 mm and more, are favourably affected by shot peening.

Gear wheels

Shot peening of gear wheels is one of the most common applications of this treatment. The field of application of gear wheels ranges from cars to heavy vehicles, from marine transmissions to small wheels used in machine tools to large wheels used in ship transmissions and mining equipment [3]. The spokes at the throat bottom of gear wheels are generally the most heavily loaded areas and should be shot peened. However, it has been shown that the small indentations caused by shot peening on the surface of gear wheels act as small oil reservoirs improving lubrication, reducing the danger of fretting, noise, chipping, scraping and, at least at low temperatures, reducing friction. Gear wheels, which must have very tight machining tolerances, can be lapped and polished after shot peening, taking care, however, that the operation does not remove more than 10 per cent of the layer of material in which the compressive stresses were induced; furthermore, gear wheels are frequently shot peened after being subjected to case-hardening treatment. The Metal Improvement Company found that the life of a hardened gear wheel, stressed with a load of 550 N/mm2, increases from 200,000 cycles before shot peening to 30,000,000 cycles after shot peening [3]. The use of high hardness shot (HRC 55-62) is recommended in the case of hardened case hardened wheels in order to produce a greater amplitude of compressive stresses. The increase in fatigue strength is generally quite substantial, often exceeding 30% at 106 cycles, particularly in the case of shot-hardened gears; excellent results can also be achieved with hardened gears and induction-hardened gears with induction-hardened teeth and throat bottom. Due to the significant differences in hardness between the case-hardened layer and the core, peening the opposite faces of the gear wheel produces a marked difference; this makes it easy to identify the case-hardened layer so that its uniformity can be verified. The Lloyds Register of Shipping estimates a 20% increase in wear resistance and fatigue strength in teeth with the use of controlled shot peening. Det Norske Veritas of Norway states that “for spur gears produced in accordance with the usual quality requirements (insignificant surface decarbonisation, unexceptional notch finish, etc.), 20% is added to the fatigue limits for shot peened parts in our calculation methods. In addition, shot peening is effective in preventing failure due to pitting of hardened, case-hardened gears. Shot peened gears show a higher pitting resistance by a factor of 1.6

compared to non-pitted gearwheels. Residual stress measurements and analyses indicate that this is the result of the high compressive stresses produced by shot peening. Calculating the fatigue life of sprockets with reference to the actual stress state (sum of the stresses due to applied loads and residual stresses) results in a 50 per cent longer life for shot-peened wheels. In fact, the residual stresses measured in shot peened gears are much higher than in standard gears.

Cost analysis

Let us now briefly analyse the economic impact of this treatment on the overall cost of a single mechanical part even though it is rather difficult to give general rules. The convenience or otherwise of shot peening is linked to a large number of factors that vary depending on the type of application envisaged, the material used, and the quantity of parts to be produced. However, it is clear that shot peening causes an increase in costs in the short term and often also in the long term. After the manufacture of a mechanical component, it can happen that the distribution of stresses following the application of external loads differs from that intended at the design stage; this difference is clearly reflected in the fatigue life of the component, which is shorter than that for which it was made. In this situation, the simplest and most immediate remedy may be the use of shot peening. The additional costs are often insignificant when compared to those that would be incurred due to the time it would take the designers to rethink a new design to solve the problem that has arisen (e.g. due to notches that are too pronounced, etc.), time that would be lost in the production of the components themselves. In industrial processes where heat and/or mechanical treatments are expected to leave residual tensile stresses, the use of shot peening is indispensable to contain the damage caused by fast crack propagation. When the additional costs of applying the treatment become excessive, shot peening can only be used for those mechanical components that fulfil special functions (e.g. transmission components). In conclusion, it can be said that shot peening leads to an increase in costs but, in the long term, and in several cases also in the short term, there is an overall saving due to an increase in the fatigue life of the parts. This saving is, however, impossible to quantify as the lower cost on the individual part is almost negligible, while the advantages lie in the prevention of breakage of the component inserted in the operating system, breakage that would block the system itself. In aerospace components, these requirements are obviously predominant, even beyond the economic factor.

Conclusions

In this editorial article, the editor wanted to bring back his knowledge, in brief, on one of the most effective treatments for increasing the strength of machine elements. The machines of the future will have to be lightweight and have components with a high strength-to-mass ratio. To achieve this requires high-level skills and knowledge, which only schools of higher education can provide. “Sublime mechanics” should be brought back to the centre. And to the future.

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