International Journal of Fatigue 33 (2011) 1477–1489

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Influence of laser polishing on the high cycle fatigue strength of medium carbon AISI 1045 steel

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ARTICLE INFO

Article history:
Received 8 April 2011
Received in revised form 20 May 2011
Accepted 5 June 2011
Available online 12 June 2011

Keywords:
Fatigue strength
Laser polishing
Medium carbon steel
Fatigue design
Life prediction

ABSTRACT

Laser polishing is a surface treatment which is becoming a feasible alternative to mechanical processes such as conventional polishing and grinding, in a number of applications including moulds and dies. Being a relatively new process the knowledge of its effects on the fatigue behaviour is very poor. This research deals with the influence of laser polishing in the absence of an inert gas on the high cycle fatigue (HCF) of AISI 1045 steel. The experimental part of the work includes tests on tensile properties, surface roughness, residual stresses together with fatigue tests of mirror and laser polished specimens. The fatigue behaviour is slightly related to the surface roughness but mostly to the microscopic properties of the surface resulting from the melting and evaporation of material and the remainder of the heat affected zone (HAZ). A theoretical study, based on the experimental results, is addressed to obtain quantitative values of the fatigue strength useful for the analysis and design of laser polished components. It will also be demonstrated that laser polishing improves the HCF behaviour of AISI 1045 steel components whose surface roughness before laser polishing is higher than a threshold value.

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1. Introduction

Laser surface treatments can be considered as unconventional and emerging manufacturing processes. Industrial applications of laser surface treatments are relatively new and limited to some special cases. However, applications are growing continuously due to the advances in automation and quality of the processed surfaces. One of the most relevant laser surface treatment processes is that of laser hardening. Laser hardening is based on the use of a high intensity laser radiation source that rapidly heats the surface of the steel to the austenitic region. Due to the high rates of heat transfer, temperature gradients are set-up which result in rapid cooling by conduction. This causes the transformation from austenite to martensite without the need for external quenching. This process is actually being used in the manufacture of automotive parts and in the die and mould industry and, being a thermal treatment, the knowledge of the mechanical properties, including improved fatigue behaviour, is good [1–3].

There are other laser surface treatment processes that have not been so widely used in industry and which are still subject to considerable research effort. This is the case for laser shot peening, which is based on the generation of shock waves by high energy radiation pulses. The result is the introduction of compressive residual stresses in the surface improving the fatigue resistance of components [4–6]. Laser shot peening can induce a deeper compressive residual stress layer and improve fatigue strength more effectively than shot peening [7]. Other processes, such as laser texturing, are based on the selective elimination of material by short, high power energy pulses (10^8–10^9 W/cm^2) vaporising part of the material and melting another part which solidifies on the edges and bottom of the crater left by the pulse [8]. The results of this process show high resolution texturing, but due to its low productivity rates and relatively high cost, it is only used for the production of high added value parts, such as medical implants or photovoltaic cells. In laser-surface alloying or LSA the laser melts a shallow region of the base metal and then additive is added and alloyed with the molten base metal. It seems that if the additives are the right ones the fatigue resistance is almost unaffected by this process [9].

Finally, the laser polishing process is based on the melting and later solidification of a micro layer of material using a laser beam as the heating source in order to obtain a smooth surface topography. The idea is to reduce the height of the surface projections by melting and evaporation of material. This process has been applied for more than ten years to the polishing of non-metallic materials, such as diamond coatings, optical lenses and silicon wafers [10,11]. There are also some studies on the application of the laser polishing process on metallic surfaces, showing good results from the economic and surface quality points of view [12–15]. Roughness reduction rates of up to 80% can be obtained with final average

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doi:10.1016/j.ijfatigue.2011.06.004

Nomenclature

HAZ heat affected zone
N number of cycles
σ_{ut} tensile strength (R_m)
σ_{yp} yield strength
$\sigma_{0.2}$ 0.2% strain tensile strength ($R_{0.2}$)
min minimum value
max maximum value
m mean value
r amplitude
l denoting laser
a, b, c, d, e measurement points in the X-ray diffraction tests
$\Delta\sigma$ stress range $\sigma_{max} - \sigma_{min}$
R fatigue ratio $\sigma_{min}/\sigma_{max}$
R_0, $R_{0.1}$, R_{-1} fatigue tests with $R = 0$, $R = 0.1$ and $R = -1$
R_a average roughness
R_{ath} threshold average roughness for 10^6 cycles
σ_n fatigue limit at 10^6 cycles in the fully reversed axial loading R_{-1} test
σ'_n R_{-1} alternating bending fatigue limit of the material
σ_6, σ_{l6} fatigue strength at 10^6 cycles in the fully reversed axial loading R_{-1} tests, mirror finish and laser polished specimens
σ'_6, σ'_{l6} R_{-1} alternating bending fatigue strength at 10^6 cycles, mirror finish and laser polished specimens
M_{ss} mean stress sensitivity
σ_{max3}, σ_{max6} fatigue strengths (maximum stress) at 10^3 and 10^6 cycles for the mirror finished specimens in a $R_{0,1}$ axial test
σ_{lmax3}, σ_{lmax6} fatigue strengths (maximum stress) at 10^3 and 10^6 cycles for laser polished specimens in a $R_{0,1}$ axial test
c_s modifying factors of the fatigue limit owing to surface roughness
c_{l3}, c_{l6} laser polishing modifying factors of the 10^3 and 10^6 cycles fatigue strength (for calculations purposes)
HCF, LCF high-cycle fatigue, low-cycle fatigue
α_3, α_{l3} reduction factors of the tensile strength for 10^3 cycles, mirror and laser polished material
α_6, α_{l6} reduction factors of the tensile strength for 10^6 cycles, mirror and laser polished material

roughness values (R_a) below 1 μm. Laser polishing is used to produce a relatively smooth surface finish in previously machined components. However, this process cannot achieve a perfectly smooth surface, and in many cases it cannot produce the degree of smoothness of a mirror finish. There are also some characteristic surface effects caused by this process, including surface pores, inclusions, and also micro-cracking, a consequence of the melting, evaporation and solidification stages [15]. Despite these surface properties, the process is still useful for moulds and dies in applications not needing a very low surface roughness.

The finishing operation of large metallic surfaces is one of the most important operations for the die and mould industry. Usually the final polishing operation is carried out manually taking more than 20% of the total manufacturing time of the entire mould or stamping die. Moreover, it must be performed by highly qualified workers, so this means high production cost and long lead times. In the die and mould industry, a skilled hand polisher needs typically more than 20 min for 1 cm^2 while it is estimated that laser polishing machines will need about one minute. However, hand polishers can reach average roughness values R_a as low as 0.005 μm, whereas current laser polishing techniques with industrial lasers, cannot provide this degree of smoothness. Nevertheless, the roughness level that laser polishing can reach is enough for many industrial applications.

In the last years there has been renewed effort into the automation of the polishing process; some studies propose a combination of abrasive techniques with robotic manipulators [16] or the application of electron beam radiation [17,18] in order to polish the surface by melting a microscopic layer of the surface. Nevertheless, these solutions present some limitations. For instance, the use of robotic manipulators requires programming and setting up each case, limiting its application when the geometry of the surface to be polished is complex. On the other hand, polishing by means of electron beam radiation implies a small working area and is only suitable for small parts. Moreover, the parts have to be placed in a vacuum chamber and the total cost of the equipment may be too high for most die and mould makers.

Therefore, laser polishing is becoming a suitable alternative to hand polishing since many workshops are already using laser systems for welding, repairing or hardening different components. However, there is almost no data concerning the influence of this process on the mechanical properties and in particular in the fatigue behaviour of laser polished components. There are two main parameters in the estimation of the profitability of laser polishing when compared with other surface finish processes; one is the saving in the final cost of the product, where laser polishing may have advantage, but the other is the expected life and here is where fatigue must be considered.

2. Scope of this research and work plan

Laser polishing is a process intended to improve the surface finish of machined components, but not necessarily the fatigue properties. In fact, the melting of a surface layer can produce gas absorption, inclusions and micro-cracking, all of which may affect the fatigue strength [15]. Also, laser polishing can be performed using an inert gas such as Ar to protect the melted surface or without inert gas, as is the case in this research. In this case the melted surface reacts with atmospheric oxygen producing a very thin layer of *Fe* oxides. It is important to point out that the evaporation and the melting of a micro layer presents an important difference between laser polishing and other treatments used specifically to improve the fatigue behaviour, as for instance laser hardening. In this sense it can be stated that laser polishing is a finish process sharing some features with laser beam welding, which is also based on the melting of material [19]. Laser polishing in this work is done without inert gas, and is the last finish process.

The aim of this paper is to obtain quantitative data on the behaviour of laser polished components in the HCF zone. These data will be presented in the form of reduction coefficients and quantitative values which can be used by designers to estimate the fatigue life of laser polished components. The work presented here focuses on medium carbon AISI 1045 steel.

A set of 70 fatigue specimens were manufactured with a surface R_a roughness of about 0.04–0.08 μm which can be considered a mirror surface finish. A subset of 45 specimens was chosen at random and laser polished with a HAZ of 100–150 μm, giving a surface Ra roughness of 0.30–0.35 μm. Four specimens were used in a static stress–strain test, confirming that the static mechanical proper-

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