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The effect of nitriding, severe shot peening and their combination on the fatigue behavior and micro-structure of a low-alloy steel

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ABSTRACT

Fatigue strength of mechanical components can be greatly enhanced by generating compressive residual stress, increasing the hardness and reducing the grain size. It is well known that while the use of mechanical treatments is able to generate an effective field of compressive residual stresses and, if severe parameters are used, to cause grain refinement, thermochemical treatments are able to increase the surface hardness. This justifies the interest in developing combined treatments, able to achieve all the just mentioned factors.

In this study, the effect of combination of severe shot peening and nitriding on the fatigue limit of a low-alloy steel is investigated. Severe shot peening was conducted by using particular processing parameters to obtain ultra-fine/nano-structured surface layers. Micro-structural observation, micro-hardness, surface roughness and XRD measurement of residual stress were performed on single and hybrid surface treated specimens including nitrided, severely shot peened, nitrided plus severely shot peened and severely shot peened plus nitrided specimens. The fatigue limit of all series was experimentally determined and compared with the as-received specimens. Severe shot peening and Nitriding improved the fatigue limit by 11.6% and 51.3% respectively. Combination of severe shot peening and nitriding improved hardening, residual stress and nitrogen diffusion with respect to the single treatment. Nevertheless, it could not guarantee further improvement in the fatigue limit as compared with the nitrided smooth specimens. The results are critically assessed by considering the local fatigue limit concept.

1. Introduction

Majority of failures in engineering materials such as fatigue fracture, fretting fatigue, wear and corrosion, are very sensitive to the structure and properties of the material surface, and in most cases failures originate from the exterior layers of the work piece. Therefore, it would be considerably effective to apply some technological process to enhance the material properties on the surface of the part.

It is well established that the fatigue strength of mechanical components can be enhanced by producing compressive residual stress, increasing the hardness and reducing the grain size. Mechanical treatments such as shot peening and thermo-chemical treatments such as nitriding are extensively used to improve fatigue, corrosion and wear resistance. Shot peening is mostly benefited by generating compressive residual stress and nitriding is mostly benefited by increasing the hardness. Both processes, nonetheless, can be benefited by the additional effect. That is to say, shot peening can also increase the hardness and nitriding is also able to produce compressive residual stress, even if there might be some doubts on the introduction of high level compressive residual stress. A positive synergistic effect, therefore, could be anticipated if these two processes are combined. In order to take the advantage of the third factor, i.e. reducing the grain size shot peening can be performed by severe parameters. While a lot of effort was made in the last four decades to reveal the manner of residual stress generation during shot peening and its effect on fatigue life, it has not been a long time that shot peening was recognized as a potential process to produce surface nano-crystallizations. The common aspect is to use special combinations of peening parameters to multiply the kinetic energy of the shot impacts in order to generate a large number of defects, dislocations and interfaces (grain boundaries) on the surface layer of treated part and consequently transform its micro-structure into ultra-fine grains or nano-structure [1]. In this case, the process is called severe shot peening rather than shot peening to emphasize the obtained micro-structural refinement at surface layers.

While there is a solid background in the literature that both shot peening and nitriding can improve fatigue behavior, their combination is less investigated. In this regard, literature can be classified into two main groups. Some researcher applied shot peening after nitriding and some other studied the reverse process:

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1.1. Nitriding followed by shot peening

Freddi et al. [2] performed nitriding on 32CrMoV13 steel specimens and subsequently subjected them to shot peening, varying shot diameter and Almen intensity in two levels. Slight improvement of fatigue limit (5–10%) depending on the peening parameters was reported for combined treatment as compared to nitriding. Croccolo et al. [3] subjected unnotched and notched 32CrMoV13 steel specimens to shot peening after nitriding. No significant enhancement of fatigue limit (only 3%) with respect to the nitrided-only specimens was reported for smooth specimens. Rolling contact fatigue behavior of the same steel was investigated after deep nitriding and following shot peening. Following shot peening could prolong rolling contact fatigue life and make the spalled pit lower and smaller [4]. Contact fatigue test performed on carbo-nitrided-only and carbo-nitrided plus shot peened gears made of AISI 4130 steel showed that damage to the gears appears after about the same testing time for both kinds of treatments but in different forms: pitting and spalling for the carbo-nitrided-only gears and micro-pitting for the carbo-nitrided and shot peened gears [5]. This combination was not always beneficial. Deterioration of surface durability during sliding rolling contact fatigue behavior of maraging steel subjected to nitriding and fine particle peening was also reported in the literature [6].

Fernandez Pariente et al. [7] Investigated the effect of nitriding plus shot peening on fatigue strength of a low alloy steel specimens containing a micro-hole, acting as a pre-crack. The threshold value of stress intensity factor increased from 14.2 MPa $m^{1/2}$ for nitrided specimen to 25.1 MPa $m^{1/2}$ for nitrided plus shot peened specimens. Terres et al. investigated the effect of nitriding and the following shot peening on bending fatigue behavior of 42CrMo4 steel. More improvement (35%) for fatigue limit was obtained by nitriding plus shot peening with respect to the nitrided-only specimens (8%). This was mentioned to be due to the hardened layer that retarded the initiation of a fatigue crack by constraining the plastic deformation [8].

1.2. Shot peening prior to nitriding

The idea here is that by increasing the grain boundary area and dislocation density, enhanced diffusion could be expected in ultrafine grained and nano-structured surface layers. That is to say in this case shot peening can be useful only if performed with more severe parameters with respect to the conventional ones, thus becoming a severe plastic deformation process.

It was shown that radio frequency plasma nitriding of stainless steel in combination with a pre-treatment by high pressure torsion results in an enhanced thickness of the nitrided layer and increased surface hardness [9]. The reason was mentioned to be the transformation of the coarse grained structure into a very fine grained one as a result of high pressure torsion. The same result was also reported by applying shot peening prior to plasma nitriding of stainless steel [10]. In addition to dislocation density increment, in this case strain induced transformation of austenite to martensite had beneficial effects to provide faster diffusion. Application of shot peening to produce plastic deformation at the near surface layer of AISI 304 austenite stainless steel before plasma nitriding led to twice thicker nitrided layer than not peened specimens and improved hardness down to a deeper region from the surface under the same plasma nitriding condition [11]. Wear resistance and corrosion behavior of nitrided 316L austenitic steel can be enhanced by employing shot peening before gas nitriding [12].

Tong et al. [13] affirmed the possibility of performing nitriding at lower temperature (300 °C) for pure iron samples by generating nano-structured surface layers through a prior surface mechanical attrition (SMAT). The much depressed nitriding temperature is attributed to enhanced nitrogen diffusion in the nano-crystalline surface layer relative to the coarse grains. It was also found that the SMAT iron sample developed a nitrided layer twice as thick as that on a coarse-grained sample under the same gaseous nitriding conditions [14].

Kikuchi et al. [15] applied fine particle peening prior to gas nitriding of AISI 316 austenitic stainless steel notched specimens. The micro-hardness values for the nitrided-only specimens were the same as that of untreated specimen. On the other hand much higher micro-hardness values were achieved by application of fine particle peening prior to nitriding. This hybrid treatment could also improve the fatigue strength as compared to nitriding. However, the fatigue strength of double treated specimens was not substantially higher than fine particle peened specimens.

In the light of this literature review, it can be concluded that regarding the fatigue strength there are few studies carried out to clarify the effect of shot peening prior to nitriding. Indeed most of these studies concerned about the capability of this combination to increase subsequent nitriding diffusion layer and surface hardness. In the case of performing shot peening after nitriding the published result is somehow controversial. Minor, major and even no considerable improvement have been reported and it is not clear when someone could expect the best. Moreover, the effect of shot peening and nitriding combination on micro-structural changes was not widely investigated. Above all, it is not yet known which sequence of this combination leads to the best results if fatigue behavior is concerned. It is therefore the purpose of this study to clarify these unexplored aspects of nitriding and shot peening combination.

In the present study severe shot peening, nitriding and their combination, considering both sequences, have been performed on steel specimens. The treated specimens have been characterized by optical and scanning electron microscopy (SEM) observation, residual stress measurement using X-ray diffraction (XRD), micro-hardness tests and surface roughness measurement. The specimens have been tested through rotating bending fatigue tests performed at room temperature. SEM observations of the fractured surfaces along with a local fatigue strength approach was applied to justify the experimental results.

2. Materials and methods

The material used in this study was low-alloy steel ESKYLOS6959. Its chemical composition is summarized in Table 1. Mechanical properties evaluated through tension test are the following: 878 MPa yield stress, 1010 MPa ultimate tensile strength and 17.7% elongation at break. Rotating bending fatigue test specimens were machined from a forging according to the extraction map provided in Fig. 1a. The forging was quenched from 880 °C in water and then tempered at 635 °C for 5 h. The specimen geometry is presented in Fig. 1b.

Five batches containing 12 specimens per each batch were prepared to obtain rotating bending fatigue limit in order to compare the effects of various surface treatments on the fatigue behavior of the studied material. Different batches with corresponding naming conventions are classified in Table 2. The first group is as-received. Second and third groups were subjected to nitriding and severe shot peening respectively. Nitriding followed by severe shot peening was applied for the fourth batch. The last group was subjected to severe shot peening prior to nitriding.

Standard steel shots S230, using an air blast machine were employed to conduct severe shot peening. The shot peening intensity measured on "Almen A" strip was 18A. Shot peening was performed with 1000% coverage to ensure surface layers are severely