



RESEARCH ARTICLE

COMPARATIVE STUDY OF THE EFFECTS OF SHOT PEENING AND ELECTROLESS NICKEL COATING ON THE FATIGUE STRENGTH OF A METALLIC MATERIAL

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ABSTRACT

This article investigates the influence of surface treatments on the fatigue behavior of a low-carbon structural steel grade E235, used for pump rotors. Three surface conditions were considered: raw material, shot peened material and shot peened material followed by an electroless nickel coating. Fatigue specimens were extracted from critical areas of the rotor in order to reproduce the damage mechanisms as observed in real service. Fatigue tests were carried out under force-controlled loading at room temperature with a stress ratio of one tenth ($R = 0.1$). The results show that shot-peening significantly improves fatigue performance, with an increase in the fatigue limit of approximately 20 to 25% compared to the raw material condition. This increase of the fatigue limit is due to the introduction of compressive residual stresses and surface hardening. In contrast, the application of an electroless nickel coating after shot peening leads to a reduction in fatigue strength, probably related to tensile residual stresses and coating/substrate interface effects.

INTRODUCTION

In industrial applications, some equipment such as pumps is operated continuously in aggressive environments. These aggressive agents may include temperature or gases such as sulfuric acid. In order to improve the fatigue performance of such equipment, surface treatments are commonly used. Among these treatments, shot peening and electroless nickel coating can be mentioned. Shot peening is a mechanical surface treatment process widely used in industry to improve the fatigue performance of metallic components (1, 2, 3, 4, 5, 6). It consists of projecting small spherical mass called shots and generally made of steel, ceramic or glass. These masses are projected at high velocity onto the surface of the component to be treated. The repeated impacts of these shots induce plastic deformation in the surface layer of the material. Shot peening can also be used for surface cleaning, for forming thin parts (peen forming), and for introducing compressive stresses into the surface layers of a component. This latter application is known as prestressed shot peening (7, 8, 9, 10, 11, 12). Prestressed shot peening is the most widely used mechanical surface treatment in the industrial field, where it has an increasing number of applications, particularly for components subjected to fatigue loading and corrosion (12, 13). The aerospace standards NF L 06-831 (December 1995) and NF L 06-832 (May 1998) standardize prestressed shot peening.

There are three surface treatment processes based on the induction of compressive residual stresses: conventional projection shot peening, ultrasonic shot peening, and laser shock peening (2). These three processes differ in their impact mechanisms, the depth of the induced stresses and the control of surface condition, but they all aim to improve fatigue resistance and the durability of mechanical components (3, 4, 13, 14, 15). Electroless nickel coating, also known as autocatalytic nickel plating, is a surface coating process based on a chemical reaction without the application of an electrical current (12). The coating is obtained by chemical reduction of nickel ions in solution, which makes it possible to achieve a uniform deposit even on complex geometries. From the standpoint of fatigue performance, electroless nickel behaves differently from shot peening. The coating acts as a protective barrier that limits chemical surface attacks, thereby reducing corrosion-fatigue phenomena. However, the process may also introduce internal residual stresses in the coating (often tensile) which can have a detrimental effect on crack initiation if the deposition parameters are not properly controlled. In the context of industrial equipment such as pump rotors, which are subjected to cyclic loading and aggressive environments, shot peening represents a relatively simple, well-controlled, and economically accessible solution for extending the service life of components.

Numerous studies have shown that this treatment leads to a significant increase in the endurance limit, which justifies its use in the energy, transportation, mechanical engineering, and chemical industries (15, 16, 17, 18). In this paper, a comparative study is conducted to guide the selection of the most suitable surface treatment among shot peening and/or electroless nickel plating. Test specimens are extracted from a pump rotor in order to perform fatigue strength tests. A low-carbon structural steel grade E235 is considered and three configurations are analyzed. The first case corresponds to the untreated (raw) material after forming. The second case concerns the shot-peened material and the third corresponds to the material that underwent electroless nickel plating after shot peening. Fatigue tests were carried out under force-controlled loading at room temperature with a stress ratio of one tenth ($R = 0.1$).

MATERIAL AND METHODS

Material: The material studied is an E235 steel. E235 steel is a low-carbon structural steel defined by the EN 10025-2 standard (hot-rolled products for structural applications). It is mainly intended for structural and mechanical applications subjected to moderate loading. In accordance with the EN 10025-2 standard, its chemical composition is presented in Table 1.

Table 1. Chemical composition of E235 structural steel (wt.% according to EN 10025-2)

Element	C	Mn	Si	P	S	N
wt.% (max)	0.17	1.40	0.55	0.035	0.035	0.012

Shape of the test pieces: For fatigue performance tests, standardized specimens are available. However, these geometries often do not take into account the actual stress state in the areas of interest, as shown in Figure 1 and Figure 2. A preliminary study was therefore carried out to determine the specimen geometry. This shape was selected based on the cracks observed in this part of the pump rotor, with the objective of reproducing as closely as possible the actual service conditions of the equipment. Figure 3 and Figure 4 respectively show the specimen after strain gauge installation and the test setup.

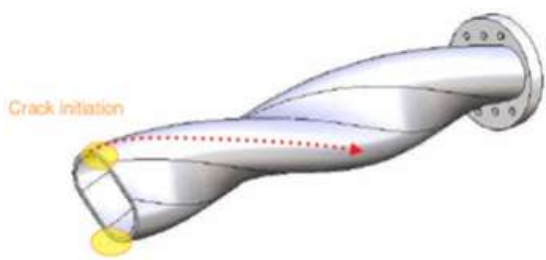


Figure 1- Identification of the zone of interest (direction of crack propagation)

Specimen



Figure 2. A specimen cut from a section of the rotor



Figure 3. A specimen after strain gauge installation

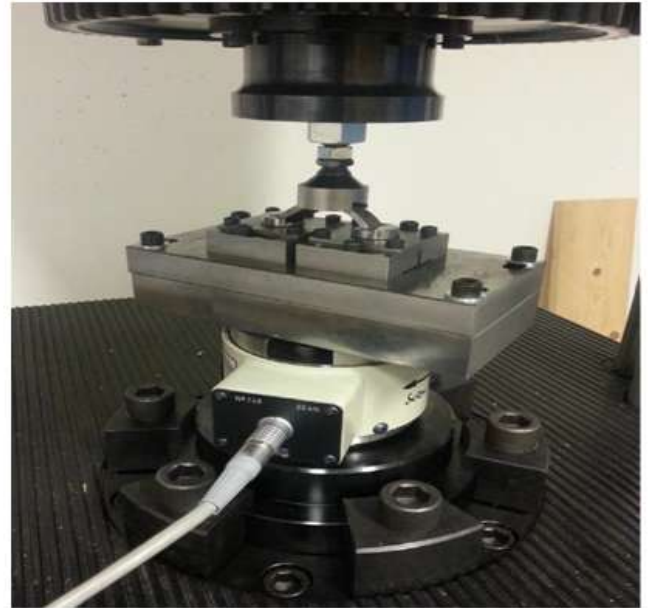


Figure 4. Test setup (picture)

Test parameters: Fatigue tests were carried out using a VibrophoreTetric machine manufactured by RUMUL. The load cell capacity used was 20 kN in static loading and ± 10 kN in dynamic loading. The maximum displacement was 8 mm, which means ± 4 mm under dynamic conditions. The fatigue test conditions are listed in Table 2.

Table 2. Fatigue test conditions

Target lifetime:	$2 \cdot 10^6$ cycles
Test temperature (°C):	Room temperature
Environment:	Air
Mechanical stress ratio:	$R = 0.1$
Stopping criterion:	$2 \cdot 10^6$ cycles or drop in frequency of 2Hz
Control mod:	Force-imposed test
Test frequency:	~ 60 Hz

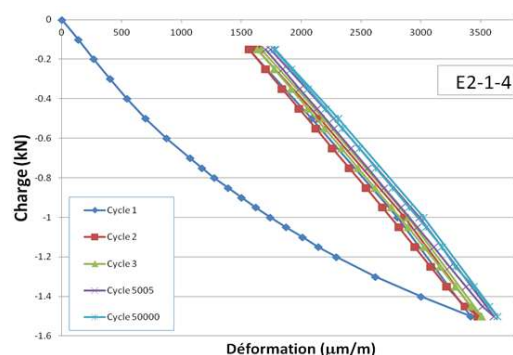


Figure 1. Phase Accommodation phase

RESULTS AND DISCUSSION

Accommodation at the beginning of tests: Initial tests were carried out to characterize the material behavior. Analysis of the curves in Figure 5 reveals the existence of two distinct phases describing the material response: a transient accommodation phase followed by a stabilization phase. During the initial accommodation phase, pronounced accommodation is observed over the first loading cycles (Cycle 1 to Cycle 3). The displacement and the change in the shape of the hysteresis loops during this period indicate microstructural reorganization. Cycle 1 exhibits the largest loop area, reflecting maximum initial energy dissipation (plastic deformation work). The evolution of the material stiffness (slope of the curves) during the first cycles makes it possible to determine whether the specimen undergoes cyclic softening or cyclic hardening under the applied stress level, resulting from changes in dislocation densities and microstructural rearrangement. The cyclic stabilization phase occurs after the initial transient phase. The hysteresis loops recorded for a large number of cycles (notably Cycle 5005 and Cycle 50000) show an almost perfect superposition. This convergence indicates that the material has reached a stable cyclic equilibrium state. In this phase, the deformation mechanisms have become constant: the energy dissipated per cycle, represented by the constant loop area, no longer varies significantly and the dynamic stiffness of the material remains constant. Most of the fatigue life of the specimen is consumed under these stabilized conditions. This behavior is typical of materials that rapidly accommodate cyclic loading to reach a stationary microstructural and mechanical state, which is essential for fatigue life predictions and component reliability calculations.

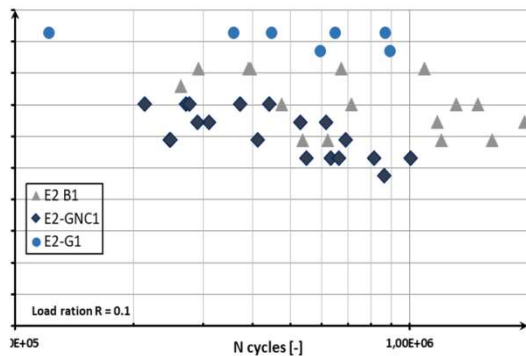


Figure 6. Evolution of the normalized fatigue limit as a function of the number of cycles to failure for the three distinct surface conditions



Figure 8 racked specimen after fatigue test

Fatigue limit determination: The comparative analysis of the fatigue test results for specimens E2-B1 (untreated part), E2-G1 (shot-peened part), and E2-GNC1 (shot-peened + electroless nickel part) makes it possible to evaluate the

influence of surface treatments on fatigue performance and behavioral stability. Figure 6 shows the evolution of the normalized fatigue limit as a function of the number of cycles to failure for the three distinct surface conditions: the untreated condition (E2-B1), the shot-peened condition (E2-G1) and the shot-peened condition followed by an electroless nickel coating (E2-GNC1). Figure 8 shows a cracked specimen after the fatigue tests. The data clearly show that shot peening alone (E2-G1) leads to the highest fatigue limit levels over the entire investigated range, reflecting a marked beneficial effect of this surface treatment. This improvement is attributed to the introduction of compressive residual stresses and surface work hardening, which delay the initiation of fatigue cracks. The measurement points associated with E2-G1 exhibit relatively moderate scatter and a fatigue life that decreases only slightly as the applied stress increases, suggesting a more stable and predictable fatigue behavior. The untreated condition (E2-B1) exhibits intermediate fatigue limit levels, with more pronounced scatter in the results. The measurement points show a gradual decrease in the number of cycles with increasing fatigue limit.

This response reflects the absence of surface strengthening mechanisms capable of delaying crack initiation. The E2-GNC1 condition, corresponding to the application of an electroless nickel coating after shot peening, shows the lowest numbers of cycles to failure. All measurement points lie well below those of E2-B1 and E2-G1, indicating a degradation of fatigue performance despite the prior shot-peening treatment. This behavior can be attributed to the introduction of tensile residual stresses, the stiffness of the coating, or coating/substrate interface effects that promote early crack initiation. Overall, these results highlight that while shot peening is an effective treatment for improving fatigue resistance, the addition of an electroless nickel coating requires careful optimization of deposition parameters in order to avoid a loss of the mechanical benefits induced by shot peening. The results thus emphasize the importance of a global approach integrating interactions between surface treatments, residual stresses, and fatigue damage mechanisms. Shot peening significantly improves fatigue performance, whereas the addition of an electroless nickel coating leads to a degradation of this performance, likely related to residual stresses and interface effects.

CONCLUSION

This study made it possible to comparatively evaluate the influence of prestress shot peening and electroless nickel coating on the fatigue performance of a low-carbon structural steel of type E235, taken from a pump rotor subjected to real industrial service loading. The experimental methodology implemented, based on specimens representative of critical crack-prone areas, made it possible to realistically reproduce the damage mechanisms observed in service. The results show that shot peening alone leads to a significant increase in the fatigue limit compared with the untreated condition. This improvement is attributed to the introduction of compressive residual stresses and surface work hardening, which delay the initiation and propagation of fatigue cracks. In contrast, the application of an electroless nickel coating after shot peening leads, under the conditions investigated, to a degradation of fatigue performance, with an endurance limit lower than that of the untreated condition. This behavior suggests that the

beneficial effects of shot peening are partially inhibited by the coating, probably due to the introduction of tensile residual stresses and coating/substrate interface effects that promote early crack initiation. These results highlight that the choice of a surface treatment must be adapted to the dominant loading mode. While shot peening appears to be an effective solution for improving the fatigue performance of pump rotors, the use of electroless nickel should primarily be considered for its corrosion and wear protection properties. Further work incorporating a coupled mechanical–environmental approach, as well as optimization of the coating parameters, will make it possible to refine the compromise between fatigue resistance and corrosion protection properties under service conditions.

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