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Potential Improvements of Mechanical Properties of Maraging Steels After Laser Shock Peening (LSP)

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Maraging steels represent a special group of precipitation-hardening steels, mainly used for highly stressed components in critical applications and for the manufacturing of die casting tools. Consequently, they are subject to different forms of load and wear which inevitably shorten their service life. Therefore, improvements of their mechanical properties and especially the resistance of the surface layer to such phenomena are of great interest. Peening techniques, such as shot peening (SP) and laser shock peening (LSP), represent a promising solution. In this paper, we present the results obtained with the surface integrity analysis on X2NiCoMo18-9-5 maraging steel before and after different sequences of LSP and heat treatment stages. The originality of the present work is that the laser treatment has been performed on a maraging steel, which brings new insights into the effects on its fatigue strength, which could be of interest to the scientific community and the industry. The main challenge is the optimization of process parameters using affordable low energy lasers. Within the present study LSP has shown promising results, supported by mechanical fatigue tests.

Keywords: *Fatigue strength; laser shock peening (LSP); maraging steels; precipitation hardening; roughness; residual stress*

1. INTRODUCTION

Maraging steels represent a special group of steels that are characterised by their excellent combination of high strength and high toughness. Upon cooling from

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the solution annealing temperature, the austenite matrix transforms to a soft and fully martensitic structure with a high dislocation density [1]. In the case of maraging steels, carbon is considered to be an impurity and is kept as low as commercially feasible since it promotes the formation of carbides, which have a negative effect on ductility and toughness. Unlike other well-known steels, these alloys achieve their high strength through artificial aging, which is performed after solution annealing. The artificial aging process, usually conducted at temperatures around 480°C [2], involves the precipitation of intermetallic compounds at dislocation sites, thus contributing to the achievement of the excellent combination of strength and toughness. Commercially available maraging steels can reach yield strengths over 2 GPa. In addition to high strength, they are characterised by high resistance to thermal fatigue, high fracture toughness, and good weldability [3]. The martensitic transformation requires a lower cooling rate; therefore, the occurrence of distortion and cracking is minimal, thus allowing for parts to be machined to final dimensions before artificial aging.

The downside of maraging steels is their high cost due to the high content of nickel, molybdenum, titanium, and especially cobalt. Therefore, maraging steels are limited to the manufacturing of added value applications and critical components [4] in aeronautical and aerospace engineering, such as helicopter drive shafts, jet engine shafts, landing gear, arresting hooks, fasteners and wing hinges. Properties, such as good machinability, dimensional stability during heat treatment, and significant resistance to thermal fatigue, have promoted the use of maraging steels in tooling applications, such as plastic moulds and die casting dies. Maraging steels are used for the manufacturing of critical mechanical parts that are subject to mechanical fatigue while the die-casting process involves a complex interaction between various forms of load and tribological phenomena, such as corrosion, erosion, soldering, and thermal fatigue. The most critical failure mode in die casting is thermal fatigue, which can cause the emergence of heat checks and stress cracks in the low cycle fatigue regime. The listed phenomena have a negative effect on fatigue life and may cause an early failure of the mechanical part.

Mechanical properties of highly stressed metallic components can be significantly improved by generating compressive residual stresses in the surface layer of the material using peening techniques [5] such as shot peening (SP) and laser shock peening (LSP). LSP is an innovative surface treatment [6], during which the surface of the treated component, usually covered with an absorbent coating and a transparent confining medium, is exposed to nanosecond long laser pulses of intense energy [7]. A schematic representation of this process is shown in Figure 1. During the laser pulse execution, the irradiated material under the laser spot vaporises and, with the further absorption of the laser energy, it ionises and transforms into plasma. The rapid expansion of this plasma generates pressure on the surface by transmitting a shock wave into the treated material. If the mechanical effect of the shock wave exceeds the dynamic yield strength of the treated metal, compressive residual stresses

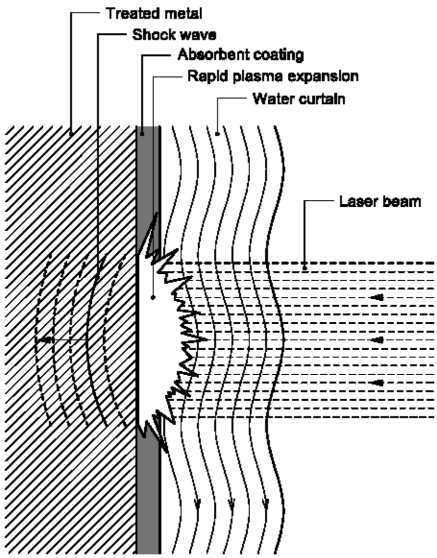


FIGURE 1
Schematic representation of the LSP process.

are generated in the surface layer. Using this surface engineering technique, compressive residual stresses can be induced to depths up to 1.5 mm [8].

While extensive research has been carried out on aluminium alloys, conventional steels and titanium alloys, very little is known about the effects of LSP on the fatigue strength of maraging steels. One of the early research papers in this context was presented by Banas *et al.* [9] who exposed maraging steel weldments to high-power short laser pulses using a Nd:YAG laser. The mechanical effect of shock waves increased the dislocation density in the heat affected zone (HAZ) that led to a 17% increase in fatigue strength after LSP. Grum *et al.* [10] analysed the effects of LSP on a die casting maraging steel, i.e. X2NiCoMo12-8-8. After LSP, compressive residual stresses up to 800 MPa were generated in the surface layer.

A well-established peening method with the aim of increasing fatigue strength is also SP, during which the surface of the treated metal is exposed to a flux of hard and spherically shaped small particles [11]. By inducing plastic deformation under the interaction zones, SP generates compressive residual stresses in the surface layer to depths up to a quarter of a millimetre. The application of this peening technique on maraging steel was analysed by Moriyama *et al.* [12] and Kawagoishi *et al.* [13] who carried out fatigue tests using a rotating bending machine. The investigation on fatigue properties and fracture mechanism of 18% Ni maraging steel showed a marked increase in fatigue strength after SP was applied.

Recent studies [14-17] on other high-strength and tool steels have shown that the implementation of peening techniques can increase wear and thermal fatigue resistance by generating compressive residual stresses and inducing strain hardening in the surface layer. In the current paper, we are presenting the results obtained with the surface integrity analysis on X2NiCoMo18-9-5 maraging steel before and after different sequences of LSP and heat treatment stages. To get a glimpse into the effects of LSP on the fatigue strength of 18% Ni maraging steel, screening fatigue tests were carried out.

2. EXPERIMENTAL DETAILS

2.1. Material properties

Experimental work was conducted on X2NiCoMo18-9-5 maraging steel with 18 % of nickel. With the appropriate heat treatment conditions, this type of maraging steel can achieve a tensile strength around 2000 MPa after the precipitation-hardening stage. From an application point of view, this material is suitable for the manufacturing of high-end structural parts in the aeronautical and aerospace industry, and in some cases even die-casting and injection moulding tools. The main mechanical properties and the chemical composition of X2NiCoMo18-9-5 maraging steel are represented in Table 1 and Table 2.

2.2. Heat treatment and laser shock peening (LSP)

Maraging steel specimens for surface layer analysis were exposed to seven different sequences of heat treatment stages and laser shock peening. The complete heat treatment process consisted of solution annealing for 1 h at a

TABLE 1
Chemical composition of X2NICOMO18-9-5 maraging steel.

Fe	C	Co	Ni	Mo	Ti	Al	Mn	Si	P	S
Bal.	≤0.03	8.0-10.0	17.0-19.0	4.5-5.5	0.5-0.8	0.05-0.15	≤0.10	≤0.10	≤0.01	≤0.01

TABLE 2
Mechanical properties of X2NICOMO18-9-5 maraging steel.

<table>
<tr><th>HTC</th><th>R_m [MPa]</th><th>$R_{p0.2}$ [MPa]</th><th>E [GPa]</th><th>ρ [kg/m^3]</th><th>HV</th></tr>
<tr><td>SA</td><td>1070</td><td>870</td><td>184</td><td rowspan="2">8100</td><td>340</td></tr>
<tr><td>PH</td><td>2050</td><td>1900</td><td>195</td><td>669</td></tr>
</table>

HTC… heat treatment condition
SA… solution annealing
PH… solution annealing and precipitation hardening
R_m … ultimate tensile strength
$R_{p0.2}$ [MPa]… yield strength
E… modulus of elasticity
ρ… material density
HV… Vickers hardness

temperature of 820°C and precipitation hardening which was conducted at a temperature of 480°C for 3 h. Solution-annealed specimens and precipitation-hardened specimens were gradually ground using SiC papers and then exposed to LSP. LSP was conducted with a Q-switched Nd:YAG laser operating at a wavelength of 1064 nm, a laser pulse energy of 2.8 J, and a laser pulse duration of 10 ns. During laser treatment, the specimens were covered with a water curtain, but no absorbent coating was used. In comparison to conventional LSP, schematically represented in the Introduction section, this technique uses lower laser pulse energy in order to avoid surface melting. This permits the laser treatment to be performed without a sacrificial layer and allows higher overlapping rates between laser spots. The laser treatment variations were based on two different laser pulse densities of 900 and 2500 pulses/cm^2. The peening treatment was performed with a single pass using a round laser spot with a diameter of 1.5 mm. LSP was once carried out between the solution-annealing stage and precipitation-hardening stage. Specimen designations are listed and described in Table 3 while the laser system equipment and the chosen mode of the laser beam path are shown in Figure 2(a) and Figure 2(b).

3. RESULTS AND DISCUSSION

3.1. Surface layer analysis

Surface roughness was analysed by measuring the arithmetical mean deviation *Ra*, the mean roughness depth *Rz*, and the maximum peak-to-valley height *Rt* of the surface profile. A Surtronic 3+ contact profilometer was used for this purpose, and the input data was processed with TalyProfile software. The surface roughness of each specimen was calculated as the average between 5 longitudinal and 5 transversal measurements. An additional brief surface roughness analysis was carried out on both untreated and laser peened specimens using a Form Talysurf Series 2 to obtain topographic contour plots.

The obtained results of the surface profile analysis are represented with two charts in Figure 3(a) and Figure 3(b), which show the surface roughness before and after LSP of the maraging steel specimens in the solution-annealed condition and precipitation hardened condition using different laser pulse densities. As can be observed, a significant increase in surface roughness occurs after performing the laser treatment. Considering both heat treatment conditions, the initial *Ra* and *Rz*, amounting to 0.2 and 1.0 μm, increased to approximately 1.0 and 5.0 TO 6.0 μm after LSP with the highest pulse density of 2500 pulses/cm^2. In contrast, the maximum peak-to-valley height *Rt* increased from approximately 2.5 to 9.0 μm. The comparison between specimens in the same heat treatment condition indicates that surface roughness grows with increasing laser pulse density.

The effect of variation of laser pulse density on the surface roughness of maraging steel in the precipitation hardened condition is clearly visible in the

TABLE 3
List of specimens and the corresponding sequence of heat treatment and LSP.

Specimen designation	Treatment-sequence description
SA	Solution annealing
SA+LSP900	Solution annealing, LSP-900 pulses/cm^2,
SA+LSP2500	Solution annealing, LSP-2500 pulses/cm^2,
SA+LSP2500+PH	Solution annealing, LSP-2500 pulses/cm^2, precipitation hardening
SA+PH	Solution annealing, precipitation hardening
SA+PH+LSP900	Solution annealing, precipitation hardening, LSP-900 pulses/cm^2
SA+PH+LSP2500	Solution annealing, precipitation hardening, LSP-2500 pulses/cm^2

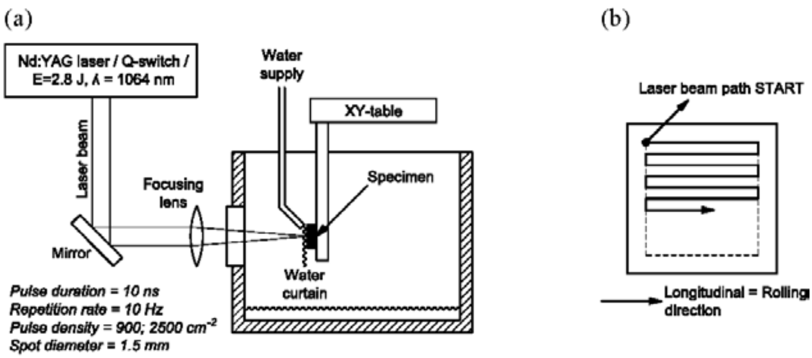
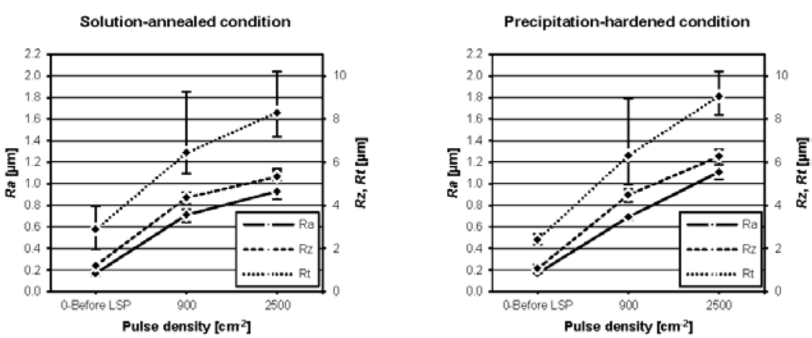


FIGURE 2
(a) Laser system and (b) laser beam path during LSP.



(a) (b)

FIGURE 3
Surface roughness before and after LSP of maraging steel in the (a) solution-annealed condition and (b) precipitation-hardened condition using different laser pulse densities.

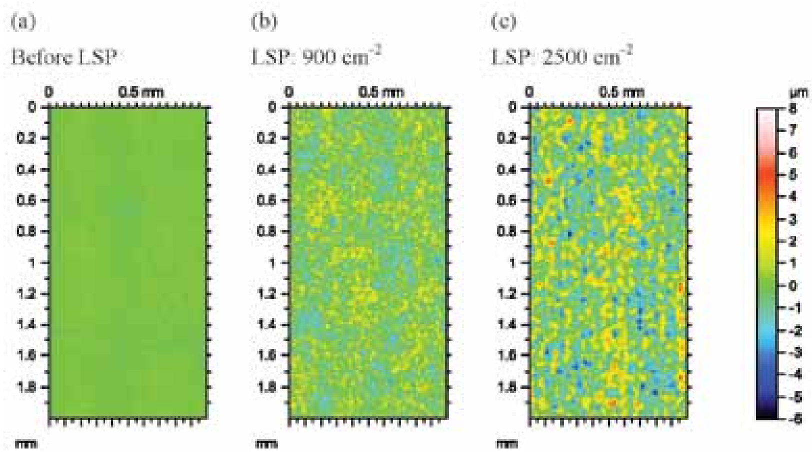


FIGURE 4
Contour plots of surface topography (a) before and (b, c) after LSP of maraging steel in the precipitation-hardened condition using different laser pulse densities.

topographic contour plots shown in Figures 4(a) to (c). After LSP, a relatively smooth maraging steel specimen, shown in Figure 4(a), with 900 pulses/cm^2 densely distributed small pits were generated on the surface leading to a surface roughness increase. This phenomenon can be attributed to a combination of plasma pressure and laser ablation, which was pronounced in our case since no surface protective coating was used. Surface topography of the mentioned laser treated specimen (SA+PH+LSP900), as is shown in Figure 4(b). By increasing the laser pulse density to 2500 pulses/cm^2, larger and deeper pits are created, as can be observed in Figure 4(c). An additional comparison of the roughness profile is represented in Figure 5.

Within this research, the in-depth distribution of surface residual stresses was conducted using the standard hole-drilling strain gage method, in accordance with ASTM E837. This method consists of drilling a small hole through the geometric centre of a strain gage rosette into the surface layer of the analysed material. In this case, an RS-200 Milling Guide was used. The material removal allows for the present residual stresses to relax and for strains to occur. The strain gage rosette, properly attached to the investigated surface area, is employed for detecting strains, which occur during material removal while drilling a hole into the surface using a milling guide. Afterward, the residual stresses and their orientation are calculated from the measured strains. Strains were detected using CEA-06-062-UM strain gage rosettes and recorded with LabVIEW. The final in-depth distributions of residual stresses in the surface layer of the maraging steel specimens were obtained with H-Drill software.

The results of the in-depth residual stress analysis can be observed in Figure 6(a) and Figure 6(b). After solution annealing (Specimen SA) low

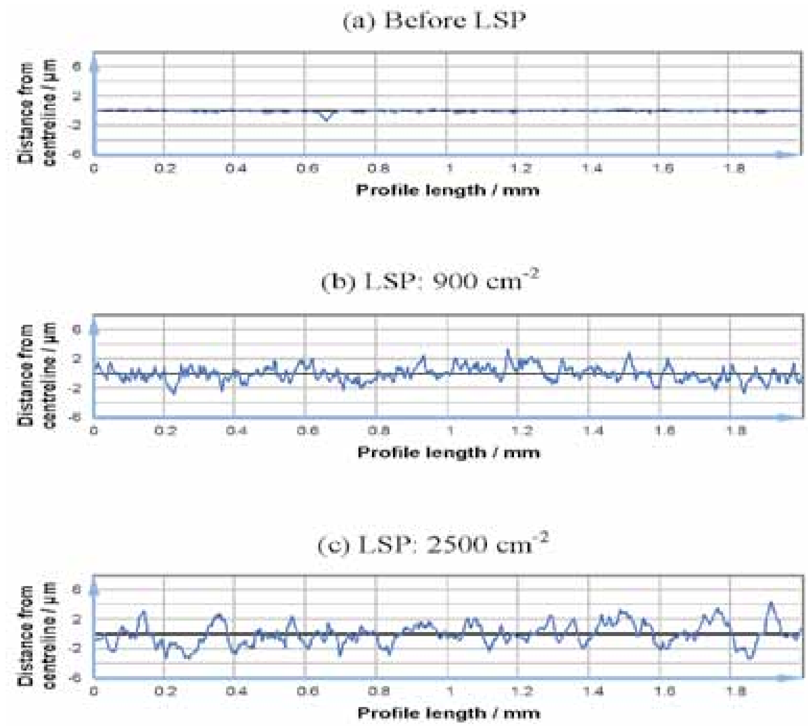


FIGURE 5
Roughness profile (a) before and (b, c) after LSP of maraging steel in the precipitation-hardened condition using different laser pulse densities.

compressive residual stresses around -60 MPa are generated in the surface layer of the maraging steel after the cooling stage. Due to thermal relaxation, these residual stresses almost disappear during precipitation hardening at a temperature of 480°C (Specimen SA+PH). According to results, compressive residual stresses were successfully generated after LSP in both the solution-annealed specimen (SA+LSP) and the precipitation hardened specimen (SA+PH+LSP). However, LSP seems to have a much deeper mechanical effect when treating maraging steel in the solution-annealed condition. Apparently, the softer state of the material allows a higher rate of plastic deformation, thus contributing to the generation of higher compressive residual stresses. Interesting results were achieved by performing the peening treatment between solution annealing and precipitation hardening (Specimen SA+LSP+PH). Even though thermal relaxation during the second stage of heat treatment obviously occurred, significant compressive residual stresses, with a surface value of around -360 MPa, were still present in the surface layer of maraging steel after precipitation hardening. Moreover, the combination SA+LSP+PH shows a greater in-depth effect in terms of compressive stress values.

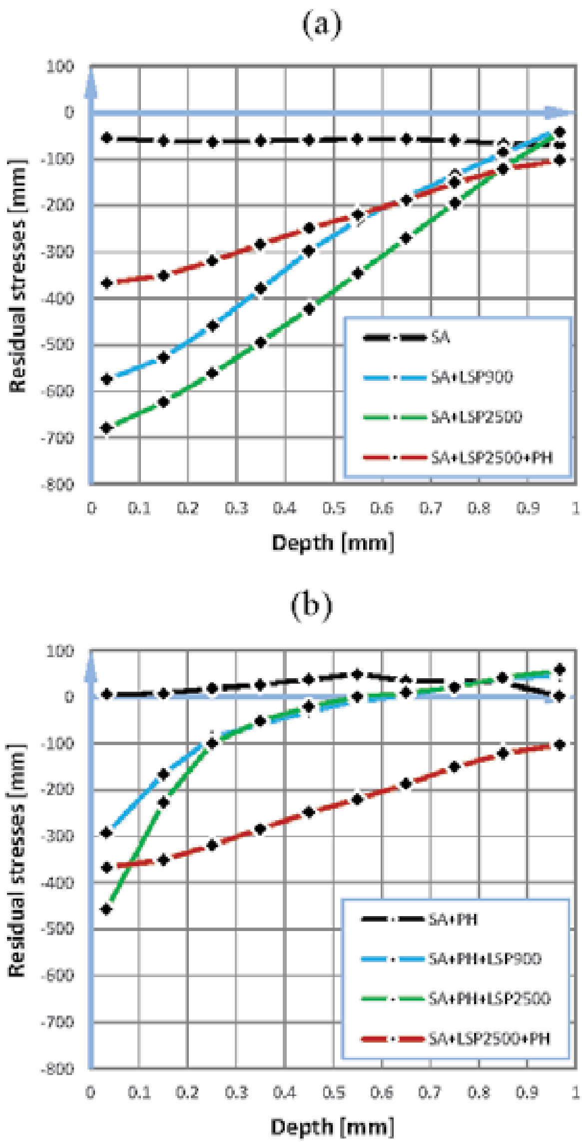


FIGURE 6
In-depth residual stress distribution before and after laser shock peening of maraging steel in the (A) solution-annealed condition and (B) precipitation-hardened condition using different laser pulse densities.

3.2. Fatigue strength analysis

The presence of compressive residual stresses itself does not insure an improvement in fatigue strength. The increase in surface roughness must be considered because surface defects may promote the initializa-

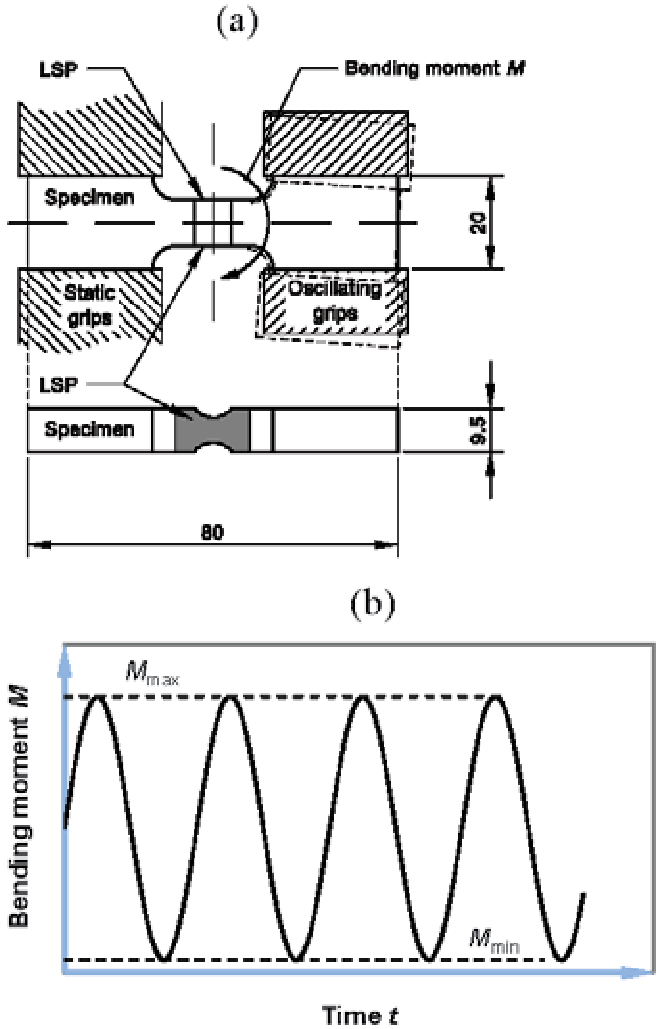


FIGURE 7
(a) Fatigue specimen geometry and loading mode, (b) time dependence of bending moment.

tion and propagation of fatigue cracks. In order to obtain insight into the effects of both the surface roughness and the residual stress state after LSP on the fatigue strength of the chosen maraging steel, screening fatigue tests were carried out using a resonant testing machine (Rumul Cractonic), which is a table model for dynamic bending-load applications with testing frequencies between 40 and 300 Hz. The kinematic conditions allow pure bending between the gripping heads. An electromagnetically driven resonator, built as a rotary oscillator, creates the

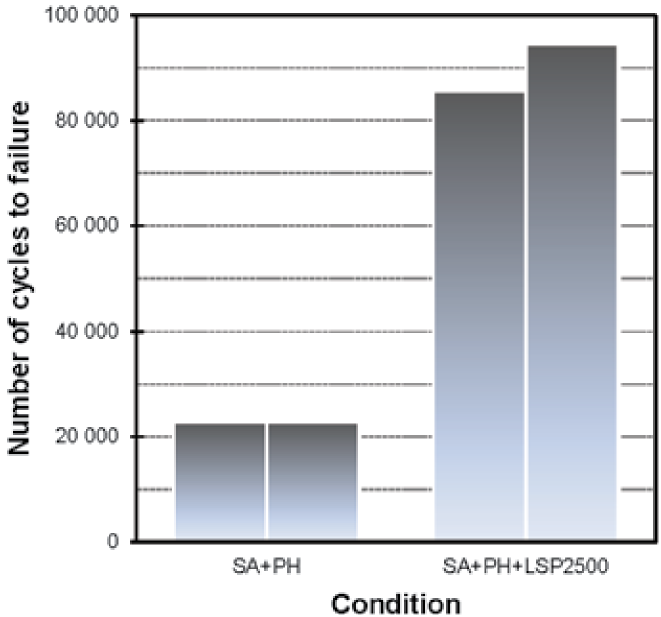


FIGURE 8
Number of cycles to failure during mechanical fatigue tests before (SA+PH) and after LSP (SA+PH+LSP2500) of maraging steel in the precipitation-hardened condition.

appropriate bending moment. In this research, the bending moment M was applied in a sinusoidal wave form at a stress ratio of R = 0.1. The bending frequency was 114 Hz while the maximal bending moment M_{max} within a fatigue cycle amounted to 78 N m. The geometry of the specimens and the loading technique are represented in Figure 7(a) and Figure 7(b). The resonant frequency, conditioned by the specimen's geometry, begins to decrease when the fatigue crack occurs. Further cyclic loading causes crack propagation and leads to a continuous decrease of the resonant frequency until final fracture. During these fatigue tests, cyclic loading was interrupted shortly after the beginning of crack propagation. The failure of the specimen was defined as the moment at which the continuous decrease of the resonant frequency began. Fatigue testing was carried out on two untreated specimens and two laser treated specimens.

The obtained results are shown in Figure 8. LSP with a 1.5 mm diameter spot and 2500 laser pulses/cm^2 increased the fatigue life of the maraging steel specimens from an average of around 23,000 to an average of around 90,000 at the current bending moment. Therefore, LSP in confined mode and without an absorbent coating might represent a method for improving the fatigue strength of maraging steels.

4. CONCLUSIONS

A surface integrity analysis on X2NiCoMo18-9-5 maraging steel was performed before and after different sequences of laser shock peening (LSP) and heat treatment stages. A brief analysis of the contribution of the laser treatment to mechanical fatigue life improvement was also carried out. The obtained results are the following:

(i) LSP generated significant compressive residual stresses in the chosen maraging steel in both the solution-annealed condition and the precipitation-hardened condition, i.e. -680 and -460 MPa;
(ii) At the current laser processing parameters, LSP generates higher and deeper compressive residual stresses in the solution-annealed condition;
(iii) The chosen sequence of LSP and heat treatment stages greatly influence the shape of the in-depth residual stress profile in the thin surface layer;
(iv) A significant proportion of compressive residual stresses, around 370 MPa, is preserved even when LSP is performed between solution annealing and precipitation hardening; and
(v) Mechanical fatigue tests on maraging steel specimens in the precipitation-hardened condition indicate a possible significant improvement in fatigue strength, even though the factor of increase of the arithmetical mean deviation of surface roughness is between 6 and 7. At the chosen bending moment, the fatigue life increase was 290%;

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