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Fatigue Performance Enhancement of Steels using Mechanical Surface Treatments

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Abstract

Mechanical surface treatments (mainly deep rolling) were performed on various steels, such as austenitic stainless steel AISI 304 and normalized plain carbon steel SAE 1045. To evaluate the effectiveness of the mechanical surface treatments, mechanically surface treated specimens were cyclically deformed at room temperature using push-pull stress-controlled fatigue and compared to the non-surface-treated condition as a reference state. Additionally, the concept, methods and effect of selected mechanical surface treatments will also be addressed in this paper. It was found that mechanical surface treatments can dramatically enhance the fatigue performance of metallic materials as compared to the non-surface-treated condition due to induced near-surface compressive residual stresses, work hardening states and increased near-surface hardnesses inhibiting or retarding surface crack initiation as well as propagation.

Key words : Fatigue, Mechanical surface treatment, Austenitic stainless steel AISI 304, Plain carbon steel SAE 1045

Introduction

It is well established that fatigue performance of components is very strongly influenced by the surface finish and surface treatment. Practically, almost all fatigue failures that occurred in industries start at the surface.(1-3) For these reasons, if the surface of materials can be modified against crack initiation, fatigue lifetime improvement can be expected. Surface treatments for fatigue lifetime improvement are therefore the advanced topics which are eventually discussed. Mechanical surface treatment is one of the most well-known methods of surface treatment for fatigue lifetime improvement. However, for Thailand's industries, particularly automotive industry, mechanical surface treatments are not well established. Only little information on mechanical surface treatment was found in Thailand.(4)

Therefore, the main purpose of this paper is to address these issues, introduce as well as suggest effective mechanical surface treatments and illustrate the effects of mechanical surface treatment (using mainly deep rolling treatment as an example) on the fatigue behavior of steels, e.g. austenitic stainless steel AISI 304 and normalized plain carbon steel SAE 1045. Near-surface properties were characterized using X-ray diffraction methods and microhardness tests. To evaluate the effectiveness of mechanical surface treatment, mechanically surface treated specimens were cyclically deformed at room temperature and compared to the non-surface-treated condition. Near-surface properties, e.g. residual stress-, FWHM-value and hardness-depth profiles of the deep rolled condition are illustrated. The effectiveness of deep rolling is presented and clarified through *S/N*-curves of the deep rolled and non-surface-treated conditions.

Concept and Methods of Mechanical Surface Treatments

Mechanical surface treatment is one of the most well-known methods of surface treatment and possesses many advantages as compared to other

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surface treatments. Mechanical surface treatment is a fast, clean, easy, low-cost (except laser shock peening) and very effective process not only for improving fatigue performance, but also wear and corrosion resistance of metallic materials.(5-7) As a consequence, mechanical surface treatments were highly investigated in various industries in the world. However, for industries and research in Thailand, mechanical surface treatment is not well established. Only very limited information on mechanical surface treatment was found in Thailand.(4) The basic concept of all mechanical surface treatments is a localized (inhomogeneous) near-surface plastic deformation (see Figures 1 (a)-(c)). Properties as well as microstructures at the surface and in near-surface regions of metallic materials are altered by mechanical surface treatments, e.g. surface topography, plasticity induced phase transformation, increased dislocation densities, induced near-surface macroscopic compressive residual stresses as well as work hardening states. These beneficial effects can inhibit or retard surface crack initiation and propagation resulting in fatigue lifetime enhancement. The amount and distribution of these altered near-surface properties depend significantly on the type of mechanical surface treatment as well as the process parameters.(8, 9) Nowadays, there are many methods for mechanical surface treatments, e.g. shot peening, ultrasonic shot peening, deep rolling or laser shock peening. The concept and some details of selected methods are shown in this paper.

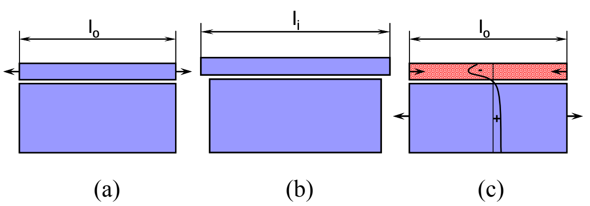

Figure 1. Schematic illustrations of the concept of mechanical surface treatments : (a) near-surface plastic deformation (b) near-surface plastic strain (c) deformed layer fixed with the bulk of material (cannot be extended).

Shot Peening

At this time, for several industries, the most well-known method of mechanical surface treatments is shot peening. Due to its flexibility, shot peening can be performed on components of almost any shape, particularly on those possessing a complex geometry. The locally and plastically deformed surface layers of the workpiece created by shot peening are a result of the impact of the individual shot particles on the workpiece (see Figure 2 (a)). Fatigue lifetime enhancement of the shot peened workpiece can be expected due to induced macroscopic compressive residual stresses as well as work hardening states at the surface and in near-surface regions. However, it is irrefutable that shot peening usually increases the surface roughness of the workpiece, especially for lower-hardness workpieces. The increase of the surface roughness can cause a deterioration of the fatigue lifetime, particularly at high stress or strain amplitude (so-called low cycle fatigue regime).(8, 9)

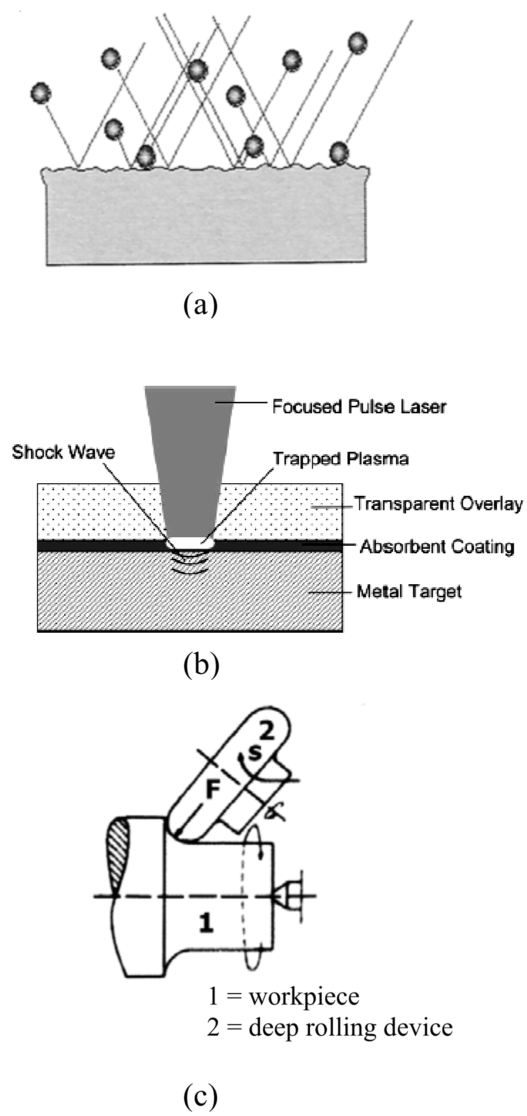

Figure 2. Schematic illustrations of selected mechanical surface treatments: (a) shot peening. (10) (b) laser-shock peening.(11) and (c) deep rolling.(9)

Laser Shock Peening

One of the relatively new methods of mechanical surface treatments is laser-shock peening which uses laser pulses with pulse duration within the nanosecond range to modify the surface layers of workpieces by means of pressure bursts, affecting near-surface regions with thicknesses within the millimetre range. The pressure wave causes plastic deformations, when the yield strength is exceeded, developing macroscopic compressive residual stresses at the surface and in near-surface regions of the workpiece.(8, 11) Figure 2 (b) shows the schematic process of laser-shock peening. However, Table 1 reveals that laser-shock peening affects also the surface roughness of the workpiece.(9, 12, 13)

Deep Rolling

The elementary mechanical process of deep rolling is the surface pressure created between the workpiece and the spherical device/ball in the contact zone (see Figure. 2 (c)). When the yield strength is exceeded, local plastic deformations occur, creating macroscopic compressive residual stresses and the associated microstructural work hardening/softening effects.(8, 14) One of the best-known benefits of deep rolling as compared to other mechanical surface treatments is the great depth of the work hardening states and macroscopic compressive residual stresses. Moreover, surface smoothening is also typical after deep rolling treatments (see Table 1).(12, 13) From these beneficial effects, deep rolling treatments today are applied in various technical fields, for example for surgical implants, for components of the steering wheels in the automotive industry as well as for turbine blades in the power plant and aircraft industry.(12)

An overview of altered near-surface properties, i.e. the induced macroscopic compressive residual stress as well as work hardening states, microhardness increase, dislocation densities and surface roughness by different selected mechanical surface treatments is given in Table 1.(13)

Materials and Experimental Procedures

Cylindrical specimens of the stainless steel AISI 304 and normalized plain carbon steel SAE 1045 with a diameter of 7 mm and a gauge length of 15 mm were prepared. The loading direction during fatigue investigations corresponds to the rolling/extrusion direction. For deep rolling, a hydraulic rolling device with 6.6 mm spherical rolling element (see Figure 3) and a pressure of 150 bar was applied at room temperature. Tension-compression fatigue tests were conducted with a servohydraulical testing device under stress control without mean stress (R = -1) and with a test

Table 1. Consequences of selected mechanical surface treatments on near-surface properties of metallic materials.(13)

	Amount of residual stress	Dislocation density	Surface microhardness increase	Maximum “case” depth	Surface roughness	Work hardening
Shot peening	$\cong \sigma_{Yield}$	very high 5-8 x 10^{11} cm^{-2}	150% AISI 304 60% SAE 1045	0.3 mm	4-8 µm	5-50%
Laser shock peening	$\cong \sigma_{Yield}$	medium	40% AA2024 30% AA7075	2 mm	1-5 µm	1-2%
Deep rolling	$\cong \sigma_{Yield}$	10^{11} cm^{-2} or lower	60%	1-3 mm	≤ 1 µm	> 20%

frequency of 5 Hz. Residual stresses and work hardening states (FWHM-values) were measured using X-ray diffraction and applying the classical $\sin^2\Psi$-method with Cr-Kα radiation at the {220} and {211}-planes and an elastic constant ½ s_2 = 60.50 x 10^{-5} mm^2/N and 60.89 x 10^{-5} mm^2/N for the austenitic stainless steel AISI 304 and normalized plain carbon steel SAE 1045, respectively.

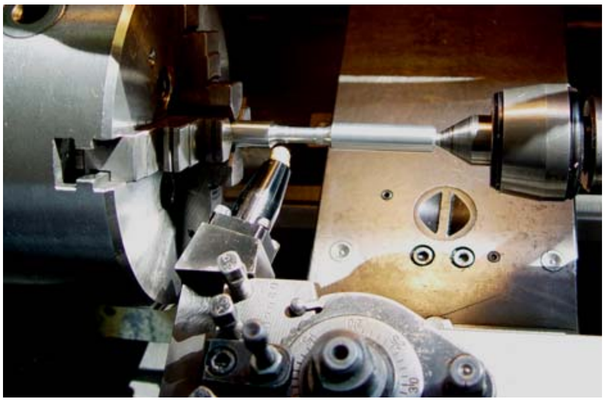

Figure 3. A hydraulic deep rolling device.

Results and Discussion

From the X-ray diffraction measurements, macroscopic compressive residual stresses and work hardening represented by FWHM values induced by deep rolling were observed at the surface and in near-surface regions as shown in Figures 4 (a) and (b). Maximum compressive residual stresses of −750 and −340 MPa were measured in a depth of 30 and 20 µm of the deep rolled AISI 304 and normalized SAE 1045, respectively. The FWHM-values in the near-surface regions increase from approximately 0.8° of the bulk to 1.7° and 1.6° of the bulk to 2.2° at the surface of the deep rolled AISI 304 and normalized SAE 1045, respectively. Deep rolling did not only lead to compressive residual stresses and pronounced work-hardening, but also increased the hardness at the surface and near-surface regions significantly as shown in Figures 5 (a) and (b). The hardnesses at the surface of deep rolled AISI 304 and normalized SAE 1045 were

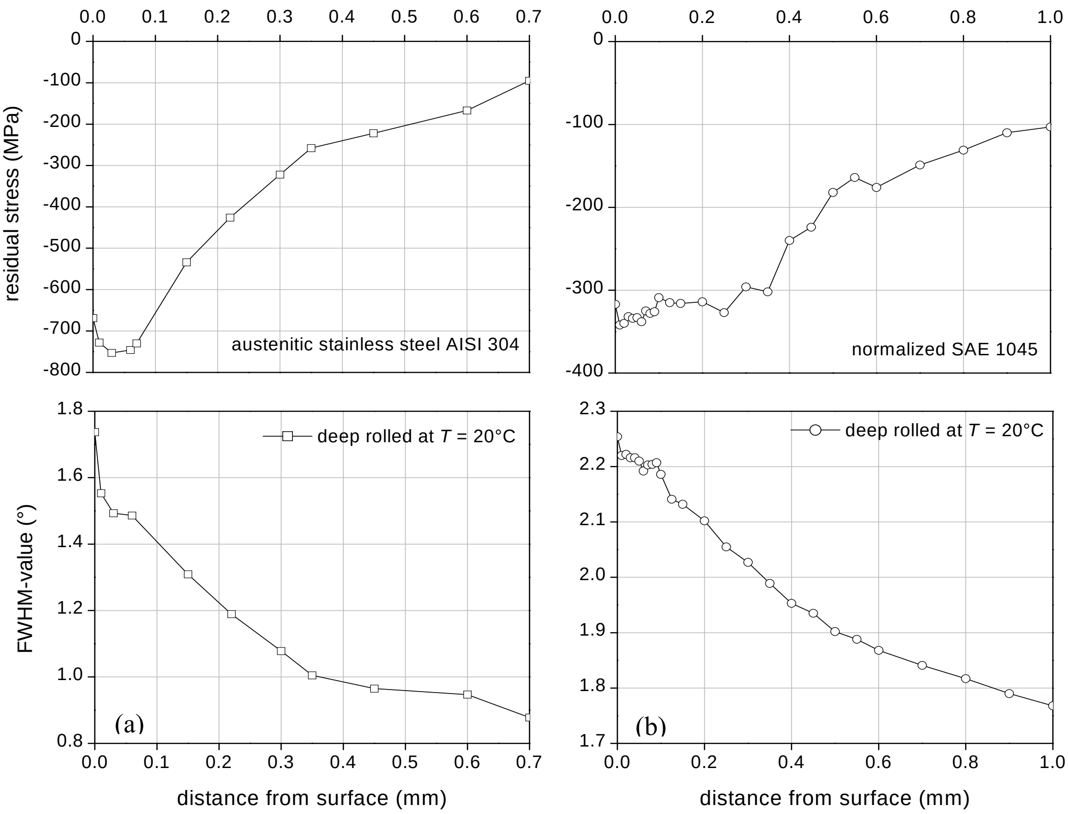

Figure 4. Residual stress- and FWHM-value-depth profiles of deep r olled (a) austenitic stainless steel AISI 304 and (b) normalized plain carbon steel SAE 1045.

increased approximately by 125 and 50 HV, respectively, as compared to the bulk material. All beneficial effects from deep rolling resulted in fatigue performance enhancement as shown in Figures 6 (a) and (b) which depict non-statistically evaluated S/N-curves of the deep rolled AISI 304 and normalized SAE 1045, respectively, as compared to the non-surface-treated condition. Deep rolling enhances considerably fatigue lifetimes and strength of austenitic stainless steel AISI 304 and normalized plain carbon steel SAE 1045, particularly in the high cycle fatigue regime (HCF). It is not only for deep rolling to enhance fatigue performance, but also for other methods of mechanical surface treatments such as shot peening as well as laser shock peening. These also improve also fatigue performance of metallic materials. Figure 7 shows an example of the number of cycles to failure of austenitic stainless steel AISI 304 after various mechanical surface treatments.

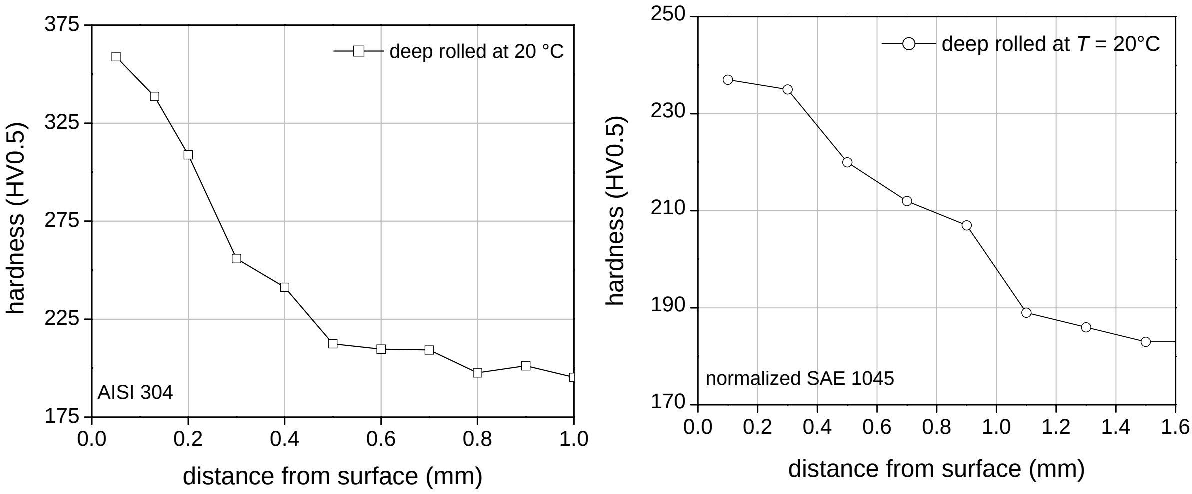

Figure 5. Hardness-depth profiles of deep rolled (a) austenitic stainless steel AISI 304 and (b) normalized plain carbon steel SAE 1045.

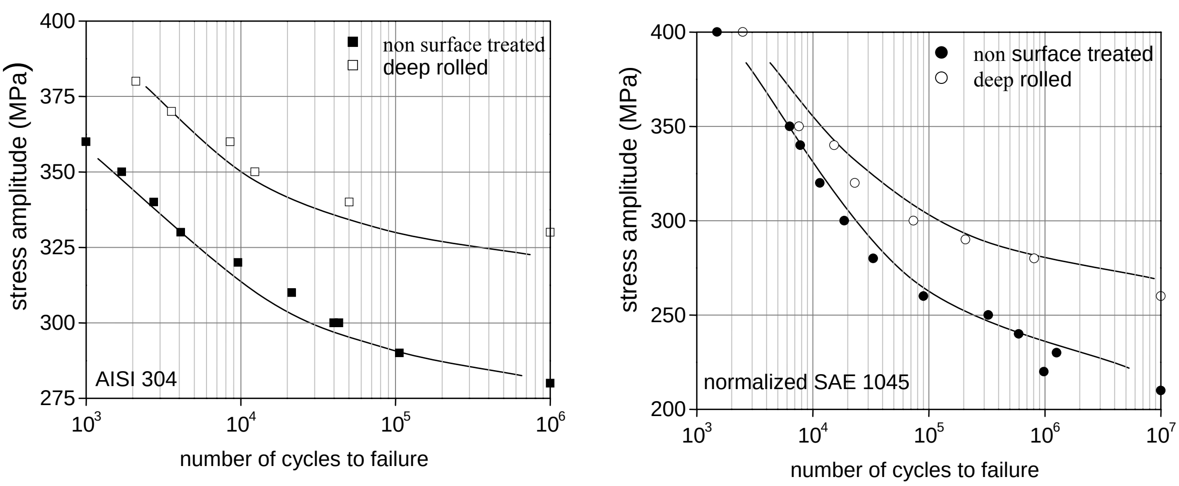

Figure 6. Non-statistically evaluated *S/N*-curves of non-surface-treated and deep rolled (a) austenitic stainless steel AISI 304 and (b) normalized plain carbon steel SAE 1045

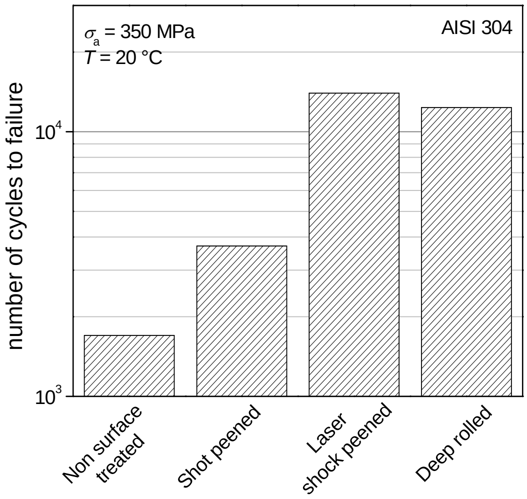

Figure 7. Fatigue performance enhancement for differently surface treated austenitic stainless steel AISI 304 ($\sigma_a = 350$ MPa, $f = 5$ Hz, $R = -1$).

Conclusion

Mechanical surface treatments possess many advantages as compared to other surface treatments, i.e. they are fast, clean, easy, low-cost and very effective processes for fatigue performance enhancement. Induced macroscopic compressive residual stresses, work hardening and increased hardnesses at the surface and in near-surface regions of austenitic stainless steel AISI 304 and normalized plain carbon steel SAE 1045 were observed after mechanical surface treatment (deep rolling). These beneficial effects serve to retard or inhibit the surface crack initiation and propagation.[15-17] and result in fatigue performance enhancement.

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