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Analysis of Residual Stress Relaxation Under Mechanical Cyclic Loading of Shot-Peened TRIP780 Steel

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Abstract. Shot-peening is a common mechanical surface treatment used in automotive and aeronautical industries to enhance life duration of mechanical parts by introducing compressive residual stresses. TRIP 780 steel fatigue type specimens are shot-peened and loaded under cyclic bending. The martensite phase transformation and the evolution of residual stresses in the different phases are determined by XRD at different numbers of cycles. A FEM model is also proposed to better understand the evolution of residual stresses in the first cycles.

Introduction

Most surface treatments aim at enhancing life duration of mechanical parts by introducing compressive residual stresses. Shot-peening (SP) process generates a compressive residual stress by deformation of the surface which is accommodated by elastic residual strains. However, those induced stresses may not be stable during the life of a part submitted to thermal and mechanical fatigue. This study deals with the analysis of mechanical stress relaxation and microstructure evolutions of a TRIP-aided steel, TRIP780 [1, 2], after shot peening and subsequent cyclic mechanical loading. This steel exhibits a multiphase microstructure (ferrite, bainite, and austenite) where each mechanical constituent participates to the global behavior [3, 4]. Austenite is a metastable phase which can transform into martensite under a thermomechanical loading.

To reach this goal, the mechanisms responsible for relaxation (plasticity, phase transformation) have to be identified. The first part presents the experimental set-up of the performed analysis and the obtained results are presented and discussed. In a second part, a FEM model using a phenomenological approach is presented in order to understand the redistribution of mechanical fields (macroscopic stress and plastic strain) during the first cycles.

Experimental methods

TRIP780 steel exhibits a multiphase microstructure (austenite, bainite and ferrite). Its chemical composition is given in Table 1. The volume fraction of initial austenite is about 13% with 70 % of ferrite and 17 % of bainite. The macroscopic yield strength of TRIP780 steel provided by ArcelorMittal is 560 MPa.

Standard fatigue type specimens cut in the transverse direction (TD) of a 2 mm thick TRIP780 steel sheet (Fig. 1) are submitted to cyclic bending.

C	Mn	Si	Fe
0.21	1.6	1.6	Bal.

Table 1 Chemical composition of TRIP780 steel in % wt (iron balanced)

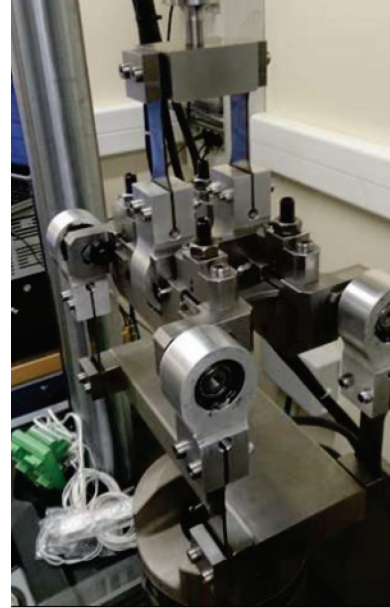
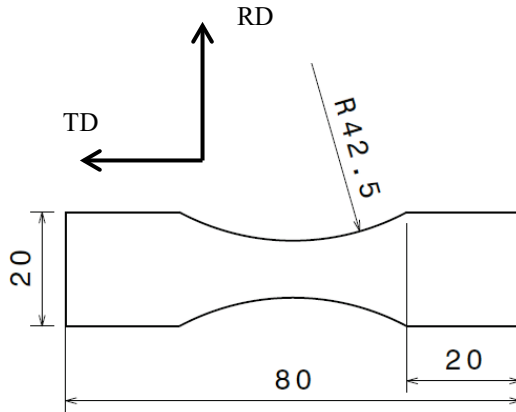


Figure 1 Specimen geometry (a). Thickness 2 mm. Dimensions in mm. Bending test bench (b)

Specimens are shot-peened in a turbine Wheelabrator machine successively on each face. The Almen intensity is F19A. The shot-peening conditions are as following: 400 μm diameter conditioned cut wire shots- hardness 700 HV, coverage 230%. The resulting Ra roughness is 4.5 μm .

The specimens are submitted to cyclic reverse bending ($R=-1$) with an imposed curvature which leads to pure bending in the area of interest. The bending test bench was developed for this study by the academic and industrial partners (Fig. 1b). The residual stresses are determined at 3 interrupted states (initial, 1000 and half-life cycles) with three targeted loading intensities (585, 600 and 650 MPa at the surface). Bending loads are calculated and calibrated from a pure elastic behavior.

Residual stresses are determined in austenite (FCC) and ferritic constituents (CC and BCC) using X ray diffraction (XRD) analysis with $\sin^2\psi$ method [5]. A D500 Siemens XRD goniometer is used to determine stress in ferritic constituents (ferrite, bainite and martensite) with Cr radiation and Vanadium filter on the $\{211\}$ planes with 40kV and 30 mA. The austenite fraction determination is carried out on the same apparatus following the ASTM standards [6]. When more than 5% of austenite is detected, residual stresses in the austenitic phase are determined with an Elphyse Set-X machine using Mn radiation with Cr filter on the $\{311\}$ planes. Residual stresses profiles are obtained by electropolishing in the transverse direction. Since the specimens are 2 mm thick, the determined stresses are corrected taking into account the layer removal [7].

Experimental results

After shot-peening, the retained austenite has transformed to martensite and a gradient of martensite and residual stresses in the specimen is determined. Figure 2 presents the austenite fraction profile after SP. Associated stress profiles of ferritic and austenitic phases are displayed in Figure 3. The determined stress in each constituent φ represents the quantity $\sigma_{xx}^{\varphi} - \sigma_{zz}^{\varphi}$, with the macroscopic value $\sigma_{zz}^{\text{Macro}}$ being equal to zero for a uniform shot peening treatment.

With 13% austenite in the as-received material, we assume that austenite is transformed in the first 200 μm . At surface, the assumption can be made that austenite is totally transformed. The shot-peened specimens show a maximum stress in compression of -600 MPa in ferritic constituent and -600 MPa in austenite phase too. As the detection threshold of austenite is 5%, residual stresses determination is carried out from 70 μm

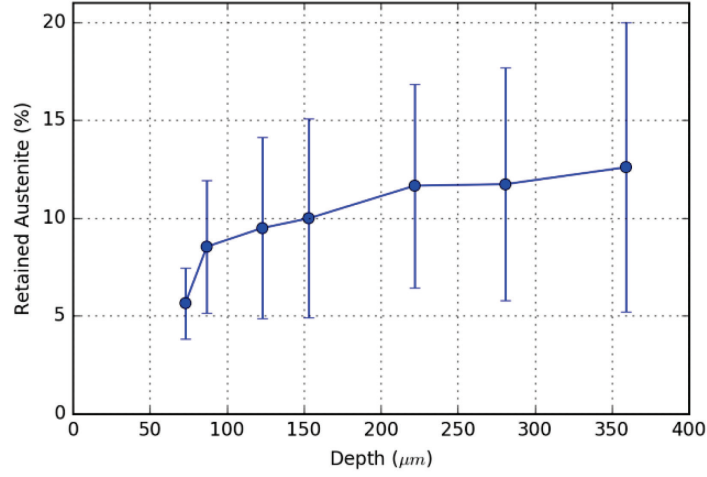


Figure 2 Initial retained austenite profile after SP

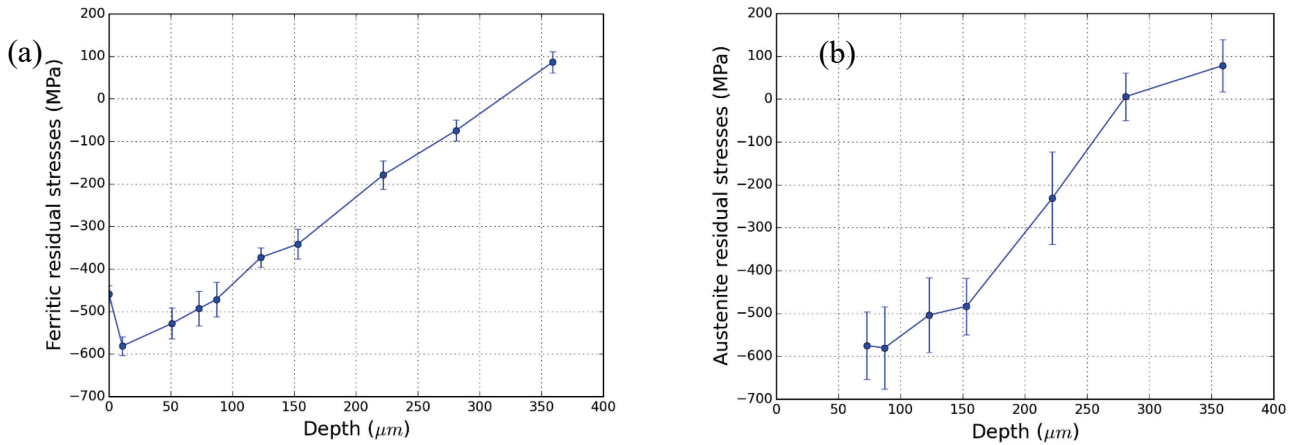


Figure 3 Corrected residual stress profiles after SP (a) in ferritic constituents, (b) in austenite in the transverse direction

In the following part, the focus is made on the macroscopic stress $\sigma_{macro}(z)$ at each depth z in the material, resulting from the averaging of the stresses in austenite σ_{xx}^{aust} and ferritic σ_{xx}^{ferr} constituents by a mixture law:

$$\sigma_{xx}^{Macro}(z) = f^{aust} \cdot \sigma_{xx}^{aust}(z) + (1 - f^{aust}) \sigma_x^{ferr}(z) \quad (1)$$

where f^{aust} is the austenite volume fraction determined by XRD and x is the measurement direction (TD in this case).

During the cyclic tests, SP specimens are submitted to an imposed curvature at 3 loads (585, 600 and 650 MPa at the surface). In Figure 4, residual macroscopic stresses after 0, 1000 and half-life cycles under the 3 loads are displayed. For the highest loading of 650 MPa (Figure 4a), residual stresses relax mainly in the first thousand cycles. The relaxation still takes place between 1000 and half-life cycles. For 600 and 585 MPa (Figure 4b and 4c respectively), relaxation in the subsurface

appears to be more important than at the surface. For each profile except 650 MPa, residual stresses reach a level of -50 MPa in subsurface (after 100 μm depth), and reach -300 MPa at the surface. For 600 MPa and 585 MPa, profiles cross at 300 μm at the value of 0 MPa. The relaxation behavior seems to be different in the first 50-100 μm than in the rest of the sample. It corresponds with the zone where austenite has been transformed by SP.

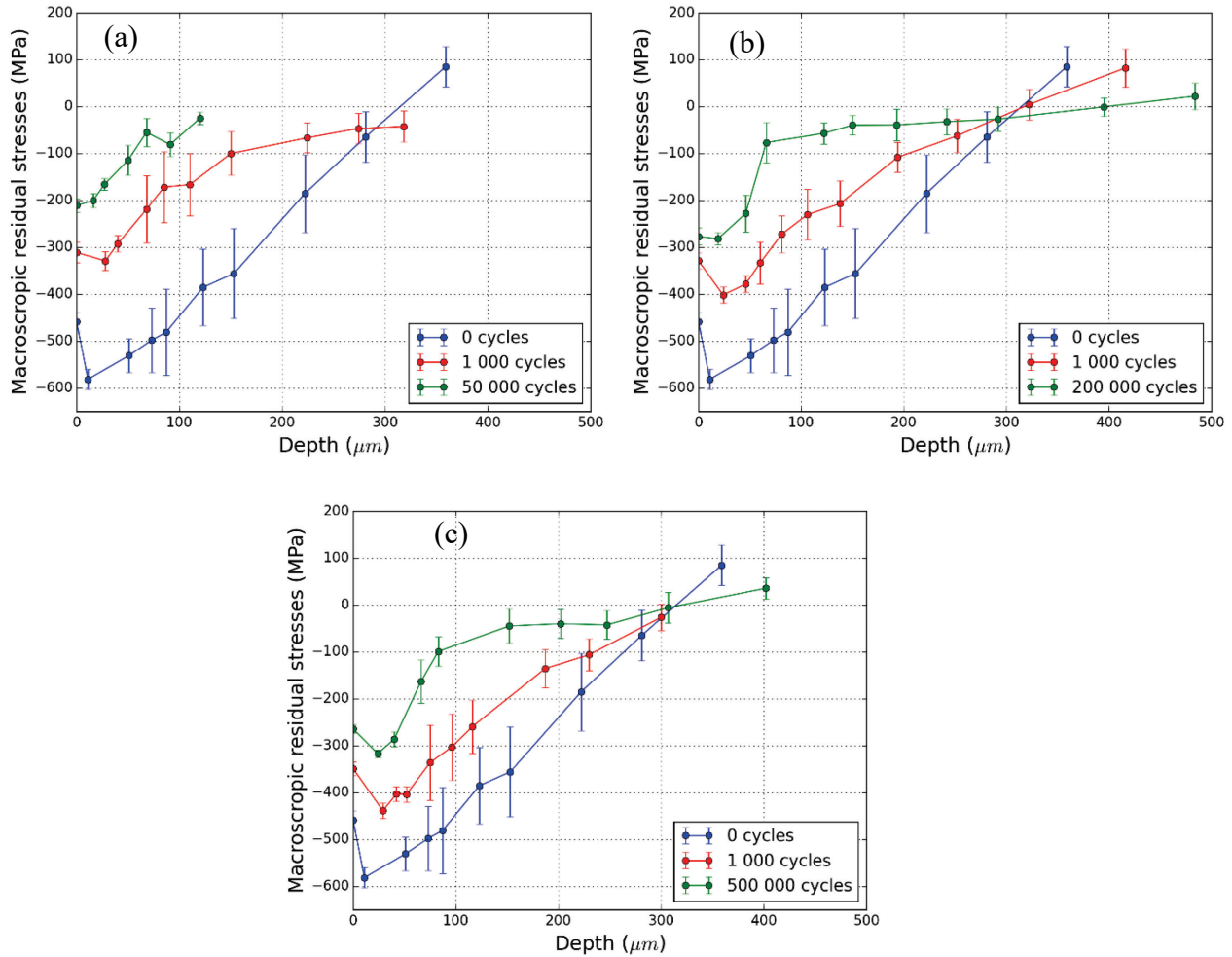


Figure 4 Relaxation for different cyclic bending loads (a) 650 MPa (b) 600 MPa (c) 585 MPa ($R=-1$).

Simulation

In this part, finite element (FE) simulations are carried out in order to understand the role of the material behavior and of the structural effect on the relaxation of a shot peened specimen. The simulations are performed with Abaqus 6.13/Standard FE software.

The first step is to model the initial mechanical state after shot-peening. Besides compressive residual stresses, shot-peening generates an important hardening at the samples surface. As a first approximation, the residual stresses are generated by the fictitious thermal method [9]. It consists in introducing fictitious dilatation coefficients α in a partitioned part, apply a fictive thermal load ΔT which generate residual stresses due to incompatible plastic strains. Plastic strain values associated with the targeted residual stresses are obtained by equation (2) (semi-infinite body hypothesis) [8]:

$$\underline{\underline{\epsilon}}^P(z) = \frac{\nu - 1}{E} \sigma_{\text{res}}(z) \quad (2)$$

In the hypothesis of an orthotropic residual stress state, dilatation coefficients are given by the following equation [9]:

$$\underline{\underline{\alpha}}(z) = -\frac{2\mu + C + K(z)}{2\mu \cdot \Delta\theta} \cdot \underline{\underline{\epsilon}}^P(z) \quad (3)$$

$$\text{with } K(z) = \left| \frac{\sigma_y}{3\epsilon_{xx}^P(z)} \right| \quad (4)$$

and C is kinematic hardening slope, σ_y the yield strength, and $\Delta\theta$ the imposed temperature change.

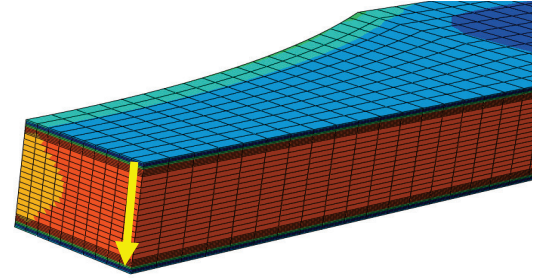
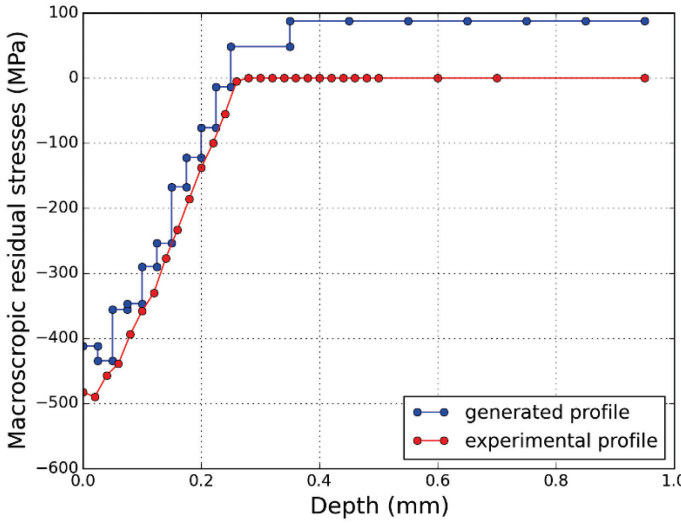


Figure 5 Simulated macroscopic residual stresses profile after shot peening and sample geometry and mesh (symmetry simplification).

The fictitious thermal method is applied to a FE model of the specimen to generate the residual macroscopic stress profile (figure 5) based on experimental data. The generated stress is slightly different from the experimental one. Indeed, the experimental profile is not self-balanced.

This method generates only the required plastic strain to generate the residual stress profile. They are about 0.3-0.4% which is far below the real plastic strain in shot-peened material (until 30-50%). The aim of this method is not to initiate the hardening internal variables. To do so, the yield strength σ_y could be change with depth in order to model some hardening effects.

Mechanical relaxation is separated in two parts [10]. Static relaxation occurs in the first bending cycles due to macroscopic strain by the superposition of residual stresses and loading. This phenomenon is modelled by a cyclic hardening law on the first 5 cycles of loading. Some numerical investigations are also presented for a material modelled with standard phenomenological constitutive laws with different hardenings.

The second part is the dynamic relaxation which needs another description of the damage mechanisms occurring at high number of cycles.

Conclusions

The initial state of shot-peened TRIP steel and the stress relaxation under 3 reverse bending loads were investigated in this study. This experimental work is followed by FE simulations which aim to dissociate static and cyclic relaxation.

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