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# Surface roughness of duplex steels: role of the microstructure

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**Abstract**

Forged duplex steels possess a highly anisotropic two-phase microstructure. Due to the mismatch of the coefficients of thermal expansion thermal stresses evolve during cyclic thermal loading which can lead to plastification of one or both phases. While the macroscopic deformation of specimens is well understood, open questions related to the effect of traction free surfaces still remain. Experimental evidence is found for a characteristic evolution of the surface roughness depending on the microstructure of the material. In this work micromechanical models based on a continuum mechanical description of the phase domains are evaluated with respect to surface roughness. Parameters for the description of the amplitude and the anisotropy of surface deformations are proposed and the model predictions are compared with experimental results.


*Keywords:* Thermal stresses; Traction free surface; Surface roughness; Autocorrelation length; Duplex steels

## 1. Introduction

Duplex stainless steels consist of almost equal amounts of ferrite ($\alpha$) and austenite ($\gamma$). Forging introduces an anisotropic microstructure with interwoven, highly elongated phase domains. During cyclic thermal loading differences in the thermal expansion of the phases lead to the development of considerable internal thermal stresses. Together with the elongated phase structure these thermal stresses cause either thermal ratchetting or plastic shake down. The influence of the in situ, temperature dependent thermomechanical properties of the phases and the geometrical phase arrangement has been investigated by micromechanical models based on the assumption of periodic boundary conditions [1,2]. The evolution of thermal stresses and macroscopic residual strains are well understood but the predictions are limited to mean bulk material properties. More recently, emphasis is put on the investigation of the deformation of traction free surfaces [3–5]. Simulations have shown a strong dependence of local residual stresses and deformation patterns on the existence of traction free surfaces [3] and experiments

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revealed a strong influence of the microstructure on the residual deformations at traction free surfaces of duplex steels under cyclic thermal loading [4–6]. Vanishing traction vectors, i.e. transition to the plane-stress state, reduce the constraint in the material next to the surface which can result in an enhanced out-of-plane deformation. Extensive research is reported on the evolution of the surface roughness of single phase, polycrystalline materials under purely mechanical loading. It is found that surface roughening is due to non-uniform plastic deformation of surface grains exhibiting local slip or rotation of grains [7–10].

This work focuses on the influence of the coarse two phase microstructure of duplex steels on the evolution of surface roughness due to cyclic thermal loading. Systematic change of the geometrical representation of phase domains in micromechanical models allows to correlate the surface roughness evolution and the phase domain size. Among the numerous parameters capable of quantitatively describing the surface roughness [11,12], the root mean square deviation $R_q$ and the fastest-decay autocorrelation length $S_{\mathrm{al}}$ are chosen to reflect the surface roughness amplitude and spatial distribution, respectively. No additional wave filtering with an a priori unknown characteristic cut-off wavelength is applied to the surface profile data in order to analyze completely the changes of the surface.

## 2. Surface roughness parameters

Surface roughness data are based on discrete surface profile data denoted as $z(x_i)$, where $x_i = i\Delta s$ for $i$ ranging from 1 to $N = l_s/\Delta s$. $l_s$ and $\Delta s$ denote the length of the scanning line and the distance between two data points, respectively. The residual surface $\eta(x_i)$ is derived as the difference between $z(x_i)$ and a reference line defined as a least-squares mean line of second order [11,12]. Based on $\eta(x_i)$ the surface roughness amplitude is quantified by the root mean square deviation of the surface data:

$$R_q = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\eta^2(x_i)}. \tag{1}$$

The spatial distribution of surface asperities is analyzed by means of the fastest decay autocorrelation length $S_{\mathrm{al}}$, which yields a statistical parameter of the general dependence of the surface amplitude at one position on the values at another position. The calculation of $S_{\mathrm{al}}$ is based on the normalized autocorrelation function (ACF) given by

$$R(\tau_i) = \frac{\sum_{k=1}^{N-i}\eta(x_k)\eta(x_{k+i})}{\sum_{k=1}^{N}\eta^2(x_k)}, \tag{2}$$

for $i$ in the range of $[0, n]$ with $n < N$ and $\tau_i = i\Delta s$. $R(\tau_i)$ depends only on the spatial distribution of the surface asperities and is independent of the surface roughness amplitude height. The fastest-decay autocorrelation length is defined as the smallest $\tau_i$ for which the ACF decays to a value of 0.2 [12]: $S_{\mathrm{al}} = \min(\tau_i)$ with $R(\tau_i) \leqslant 0.2$.

Experimental evidence shows that the spatial distribution of surface asperities strongly depends on the microstructure and $S_{\mathrm{al}}$ correlates to the characteristic length scale of the microstructure, e.g. mean grain or phase domain size [5,8]. In order to elucidate this correlation artificial test surface profiles are generated. First, a list of intersection lengths is generated which is based on a log-normal distribution of the intersection lengths of a test line with grain or phase domain boundaries. Parameters of the log-normal distribution are the mean intercept length as a measure of the characteristic length scale of the microstructure $l_c$ and the standard deviation $\sigma$. Random values are assigned to each intersection which define either a local plateau (random plateau model, RPM) or a local slope of the profile (random slope model, RSM). The signs of the random values are chosen so that the surface profiles are oscillating around a mean center line. Dividing each intersection length by $\Delta s$ yields a discrete number of data points to which respective surface amplitude values are assigned. Finally, the surface profile values are shifted slightly which simulates small random surface fluctuations. Examples of RPM and RSM surface profiles are shown in Fig. 1. For the RPM each grain or phase domain can deform completely independently of its neighbor whereas for the RSM the deformation obeys the compatibility conditions and no jumps of the surface pro-