Engineering Failure Analysis 94 (2018) 33–40

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Review

Impact of residual stresses on mechanical behaviour of hot work steels

Jamal Fajoui[a,*], Mohamed Kchaou[b], Amira Sellami[b], Samuel Branchu[a], Riadh Elleuch[b], Frédéric Jacquemin[a]

[a] *Institut de Recherche en Génie Civil et Mécanique, Université de Nantes - Centrale Nantes, 58 Rue Michel Ange, BP 420, Saint-Nazaire 44606, France*
[b] *National Engineering School of Sfax-LASEM, University of Sfax, Sfax BP W3038, Tunisia*

ARTICLE INFO

Keywords:
Hot forging steel
Residual stress
Numerical simulation
Heat treatment
Machining effect

ABSTRACT

This paper presents a multi-scale analysis of the mechanical behaviour of hot work steels taking into account the effect of residual stress generated by the initial microstructure and the external load and induced industrially by heat treatment and machining process. The methodology is based on: i) laboratory study to evaluate the macroscopic behaviour of the material, ii) numerical simulation based on finite element and homogenisation approaches to evaluate the material's microstructure complexity and characterize the residual stress distribution, iii) industrial tests during pretreatment and forging process of valve gas parts in order to complete the results obtained at laboratory scale. It was proved that residual stress induced by the initial microstructure of the hot steel material has significant effects on the stress behaviour of the hot forging steel under static tensile load. Besides, the residual stress generated during the manufacturing process affected more significantly the stress distribution on the die surface than the heat treatment, inducing residual stress close to plastic deformation.

1. Introduction

In hot forging process, the tool's surface is assigned by cyclic thermo-mechanical solicitations. The severity of the loading during process has an important consequence on the tool's performance which is determined by inadequacy of factors such as die geometry and design, forging operations, etc. [2]. Besides, the history of machining process and heat treatment which induces residual stress on the surface has an important effect on the tool's service [28]. The superficial damages manifesting especially as fatigue cracking and wear depend on the nature and the level of the generated residual stress [12, 22]). Many studies have assessed the residual stress induced by manufacturing operations (machining, polishing, …) and thermal treatment but the effect of the microstructural heterogeneity and its interaction with local residual stress are less reported [11, 16]. Nevertheless, few research used X-ray diffraction (XRD) method correlated to the forging process and took account of the history of the hot work steel treatment and machining [23]. Furthermore, some authors have developed phenomenological models giving qualitative results of the effect of residual stress on the mechanical behaviour of the H11 and H13 steels for a wide range of loading paths under service [4, 9]. Although these models don't take into account the polycrystalline nature of the material or the physical mechanisms of plasticity at the scale of the microstructure. For those, it is important to understand the influence of the microstructural heterogeneity on the mechanical response of the hot work steel under simple and complex loadings.

* Corresponding author.
E-mail address: jamal.fajoui@univ-nantes.fr (J. Fajoui).

https://doi.org/10.1016/j.engfailanal.2018.07.020
Received 23 November 2017; Received in revised form 19 March 2018; Accepted 20 July 2018
Available online 23 July 2018
1350-6307/

Table 1
Chemical composition of the hot work steel.

Element	C	Mn	Si	Cr	W	Mo	V	P	Fe
Hot work steel	0.38–0.41	0.44	1.09	5.4	0.01	1.41	0.95	0.015	Balance

In this work, an approach based on laboratory tests coupled with a numerical simulation based on a scale transition approach will be used in order to study the effect of residual stress on the mechanical behaviour of X40CrMoV5-1. This model takes into account different material's heterogeneities like crystallographic and morphologic texture, slips systems, initial residual stresses, etc. Industrial tests will complete this analysis to correlate the residual stress induced by the material anisotropy to the machining and pretreatment effect on the hot work steel.

2. Experimental details

2.1. Mechanical decoupling approach to study residual stress on hot work steel

2.1.1. Material and techniques

In this study, the investigated material is a martensitic hot work steel, used for hot forming tooling. The chemical composition is detailed in Table 1. For the monotonic tensile tests, four samples were carried out at different levels of strain (1%, 1.5%, 4% (rupture)) in order to characterize different mechanical properties. Fig. 1 shows the used samples, according to the NF A03-154. Thereafter, residual stress induced by the mechanical solicitation and the crystallographic texture was analyzed.

Samples of 70 mm large, 12 mm width and 2 mm thick were cut for static tensile tests. Cylindrical samples with 8 mm diameter and 70 mm useful length were used for tension-compression-tension cyclic tests to better understand the cyclic behaviour of the studied steel. These tests were carried out with 0.01 s^{-1} imposed strain rate.

2.1.2. Stress-strain evolution

Fig. 2.a shows the stress-strain evolution of the hot work steel under tensile test. Mechanical properties are summarized in Table 2. These properties will be exploited in the numerical modeling (next section).

Fig. 2.b shows the hysteresis evolution of the cyclic behaviour of the hot work steel. It also made the definition of the hardening parameters possible in the numerical part.

2.1.3. Analysis of residual stresses

X-Ray diffraction technique was used to quantify the macroscopic residual stresses. It was performed with a four circles XRD 3003 PTS SEIFERT goniometer using K_α chromium radiation (2.28 Å wavelength) with a 1 mm diameter collimator. XRD measurements were taken at {211} crystallographic reflection of the ferrite phase (α-Fe) corresponding to a theoretical 2θ position equal to 156.105°. Diffraction peaks have been fitted with a pseudo-Voigt function taking into account the $K_{\alpha1}$–$K_{\alpha2}$ contribution in order to determine the 2θ peaks position, evaluate the background noise and obtain peak intensities. A Khi goniometric assembly with a linear detector was used. Diffractograms were carried out for 16 tilt angles ψ varying between - 48 and 45° and for two azimuthal angles φ = 0 and 90°. Macro residual stresses were estimated by the $\sin^2\psi$ method. Another parameter used to characterize peak broadening is the Full Width at Half Maximum (FWHM) [21], which can give a qualitative evidence upon the dislocation network state. Measured strain can be expressed using Eq. (1).

$$\langle \varepsilon(hk\ell,\phi,\psi)\rangle_{V_d} = F_{ij}(hk\ell,\phi,\psi)\,\sigma_{ij}^{I} \tag{1}$$

$F_{ij}(hk\ell,\phi,\psi)$ are the diffraction elastic constants for the $\{hk\ell\}$ reflection and V_d is the average over diffracting grains for the $\{hk\ell\}$ reflection in the direction (ϕ,ψ). σ_{ij}^{I} is the macroscopic stress tensor. In our case, $^1/_2 S_2(211)$ is equal to 5.624510^{-6} MPa. Macro-residual stresses (type I) are obtained from this measured strain. After each tensile test, the FWHM and residual stress values are

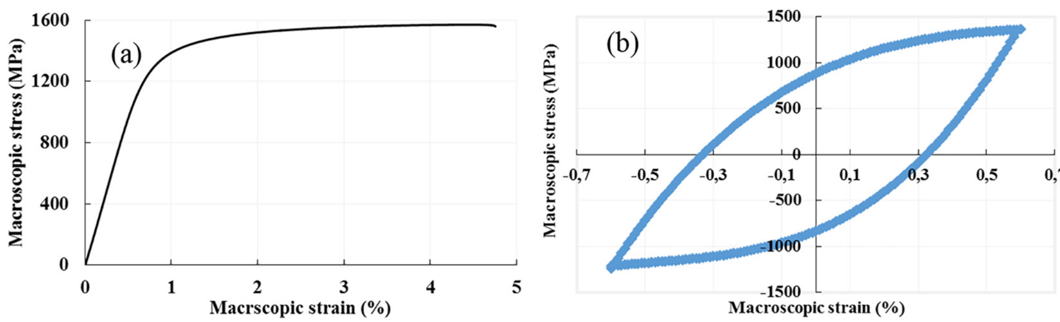

Fig. 1. Experimental stress–strain curves of the hot work steel: a) during monotonic and b) cyclic loading.