Effect of strain rate and reformed austenite on mechanical properties of AISI 415 stainless steel

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Abstract
Hydraulic turbine blades are exposed to cyclic loading which favors formation and propagation of fatigue cracks. Due to different in-service loading regimes, the crack tip is subjected to a range of strain rates. The present study proposes an experimental investigation of the mechanical properties of a 13%Cr-4%Ni martensitic stainless steel at strain rates ($\dot{\varepsilon}$) ranging from 4.7E-6s^{-1} to 6E-2s^{-1}. The $\dot{\varepsilon}$ was chosen to simulate plastic deformation rate at the crack tip for load cycles frequency ranging from 0.3 to 35 Hz. Two heat treatments were applied to the alloy to obtain a martensitic microstructure containing 2% and 20% of reformed austenite (RA). For the sample containing 2% of RA, increasing $\dot{\varepsilon}$ resulted in a difference in yield strength (σ_y) and ultimate tensile strength (UTS) of 10% and 7%, respectively. As for the sample containing 20% of RA, an increase in the RA content had no significant effect on the σ_y strain rate sensitivity. On the other hand, it reduced the UTS strain rate sensitivity to 1%. These results indicate that σ_y is strain rate sensitive for both tested microstructure. Results also show that presence of RA increased 23% the uniform elongation as compared to microstructure containing 2% of RA.

1. Introduction
Hydraulic turbine runners are critical parts of power generator plants. During service, turbine blade runners are exposed to cyclic loads which may result in component cracking. The load spectrum characteristics of the service conditions is composed of high frequency but small amplitude cyles and of low frequency but larger amplitude cycles. This leads to a potential combination of high and low cycle fatigue damages, both mechanisms caused by local plastic deformation at the tip of the crack. The variation of plastic strain amplitude and load frequency is leading to a variation in strain rate ($\dot{\varepsilon}$). Based on the work of Khodabakhshi et al. [1] the mechanical behavior of AISI 410 martensitic stainless steel can be highly sensitive to the $\dot{\varepsilon}$. Huang et al. [2] proposed that this behavior is due to multi-core structure of screw dislocations in BCC structure. The AISI 415 alloy (a 13%Cr-4% martensitic stainless steel), as revealed by the work of Godin et al., typically contains between 1% to 20% volume fraction of finely dispersed RA that forms during the tempering treatment [3]. The RA is known to accommodate strain by transforming into martensite under a mechanism called transformation induced plasticity (TRIP). Zhang et al. [4] observed this TRIP effect, in a 13%Cr-4%Ni low carbon martensitic stainless steel containing 20% of RA, with in-situ synchrotron high-energy X-ray diffraction performed during a tensile test. To the best of authors' knowledge, the influence of RA content on strain rate sensitivity of the tensile properties of the 415 stainless steel has not been previously investigated. The synergetic effects of the RA content and of the $\dot{\varepsilon}$ on the σ_y, UTS and elongation have yet to be studied. To this end, tensile tests have been carried out on a 415 alloy containing 2% RA at three strain rates and compared with the results obtained for the same alloy but containing 20% of RA.

2. Results
The strain rates at which the tensile tests were performed, were choosen to approach the strain conditions at the tip of cracks (4.7E-6 s^{-1}, 2.5E-4 s^{-1}, and 6E-2s^{-1}). The strain rates were estimated using the model of Zhao et al. [5] applied at two stress intensity factor ranges (ΔK) of 6 MPa.m$^{0.5}$ and 15 MPa.m$^{0.5}$, two load ratios (0.1 and 0.7) and three frequencies (0.3 Hz, 3.5 Hz, and 35 Hz). The engineering stress versus engineering strain curves are provided in the **Fig. 1** a and **Fig. 1** b. **Table 1** provides the mechanical properties mesured from the tensile tests performed on the material containing 2% and 20% of RA respectively. Results show that, in the case of the material containing 2% of RA, increasing $\dot{\varepsilon}$ from 4.7E-6 s^{-1} to 6E-2 s^{-1} resulted in an increase of 10% and 7% in the the σ_y and the UTS, respectively. As for the samples containing 20% RA presented, increasing resulted in a 11% and 1% augmentation of the σ_y and

UTS, respectively (see **Table 1**). The yield strength is strain rate sensitive for both studied microstructure. However, the strain rate sensitivity of the UTS is different for the different microstructure, with the material containing 2% of RA being the most sensitive to $\dot{\varepsilon}$. The presence of RA decreased the UTS strain rate dependency. Between the yield and the UTS the plastic behavior of the two microstructure are quite different as shown in **Fig. 1** a & b. The 2% RA sample is sensitive to $\dot{\varepsilon}$ during the uniform deformation. Huang et al. [2] explained a similar strain rate sensitivity in BCC iron single crystal based on the general knowledge that screw dislocation move slowly in BCC because of their multi-plane core structure. For the sample containing 20% of RA the strain rate sensitivity is insignificant. The important role of austenite during plasticity could explain the strain rate insensitivity of the sample containing 20% of RA. The tensile test results of Zhang et al. [4] performed with in-situ synchrotron high-energy X-ray diffraction showed that the austenite is the first phase that deforms. Also it has been reported by the same team that RA greatly contributes to strain accommodation until UTS. Since the austenite deforms by TRIPing, a diffusionless mechanism, it could explain that the global material plastic behavior is less sensitive to $\dot{\varepsilon}$. In addition, the remaining martensite, which is strain rate sensitive, experience less deformation. The instantaneaous work hardening (n_i) behavior as a function of the plastic deformation are also different as it is shown in **Fig. 1** c & d. Starting from a strain of 0.01, the evolution of the strain hardening coefficient, $dn_i/d\varepsilon$, is nearly 0 for the materialcontaining 2% of RA. It droped rapidly from values above 0.2 to a constant value of 0.05 where the material behaves as if it is perfectly plastic. In comparison, the strain hardening behavior of the material containing 20% of RA is significantly different. At a strain of 0.01% , the strain hardening coefficient is decreasing gradually ($dn_i/d\varepsilon \neq 0$). A continuous hardening behavior is observed until UTS is reached. This hardening could be related to a decrease in austenite content as it TRIPs into martensite as observed in the work of Dastur et al. [7]. Post morten measurements of the austenite content by XRD on the material tested at 6E-2 s^{-1} revealed an austenite fraction of 4.5% supporting this explaination.

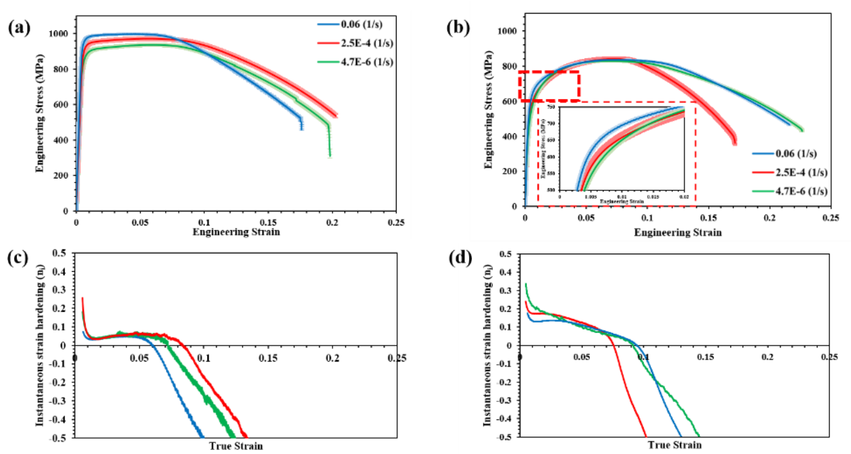

Fig. 1 Represents (a & b) engineering stress versus engineering strain (including the error range as tests were duplicated twice), (c&d) instantaneous strain hardening for samples containing (a&c) 2% RA and (b & d) 20% RA. The tensile results for 2.5E-4 (s^{-1}) test on 20% RA sample is used from Harandizadeh et al. [6] research on the same batch of AISI-415.

Moreover, the uniform elongation for the samples with 20% RA is enhanced 23% compared to 2% RA containing samples for all the applied strain rates (see **Table *1***). These observations show the influential effect of RA on uniform elongation and n_i.

Table 1. Tensile properties of samples with different RA fraction tested at various strain rates

Strain rate (1/s)	Yield strength (MPa)		UTS (MPa)		El% at UTS	
	2% RA	20% RA	2% RA	20% RA	2% RA	20% RA
4.7E − 6	850.0 ± 9	529.0 ± 8.5	935.0 ± 2.0	829 ± 0.5	7.00 ± 0.25	9.00 ± 0.25
2.5E − 4	872.0 ± 17	577.0 ± 10	971.0 ± 6.5	856 ± 16.0	7.70 ± 0.30	7.80 ± 0.24
6E − 2	924.0 ± 5	610.0 ± 4	999.0 ± 5.0	838 ± 6.0	5.95 ± 0.05	9.50 ± 0.13

3. Conclusions

Tensile tests at three strain rates were performed on alloy 13%Cr-4%Ni heat treated to reach two different microstructures. The main finding revealed by a comparison of the postyielding plastic behavior is that the presence of 20% RA reduces the strain rate sensitivity of the alloy. Nevertheless, the yield stress was found strain rate sensitive for both microstructure with highest values obtained at the higher strain rate.

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