

Fatigue properties of strained very thin 304 stainless steel sheets

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ABSTRACT

This paper aims to study the properties of 300 μ m thickness 304 stainless steel. This research topic was selected considering the high demand for the production of small products such as smart phones, solar systems, hard drives, etc. Stainless steel was chosen for its low cost, suitable weight, and good mechanical properties in terms of strength and deformation compared to other materials. However, specimen size and strain may affect the results achieved. In this study, the effects of 2% and 5% strains on the fatigue strength of very thin 304 stainless steel sheets were investigated. Fatigue samples were cut into dumbbell-shapes with a rectangular cross-section as per ASTM E8. The tensile testing results showed that 300 μ m thickness heat-treated specimen sheets had less strain hardening with clear evidence of yielding. The fatigue test showed that higher strain values lengthened the fatigue life cycles of the stainless steel specimens. From this study, it can be concluded that tensile strain can improve the fatigue strength of very thin 304 stainless steel sheets.

Keywords: Thin sheet; tensile properties; hardness; fatigue strength; fracture behaviour.

INTRODUCTION

Owing to the fast-paced technological development, stainless steel is widely used in many industries. The properties of stainless steel make it suitable as a component in many industrial applications such as in chemical as reported by Marques et al. [1] and automotive industries as reported by Wright, Lei et al., Ha et al, Shah et al. and Jamil et al. [2-6], electronic devices as mentioned by Lee et al. [7], medical instruments as reported by Hadrboletz et al. and Connolley et al. [8, 9], and other industries as mentioned by Bell, Nilsson and Molak et al. [10-12]. The popularity of stainless steel can be attributed to its ability to withstand high stress and operate at high temperatures. In recent years, the market demand for products such as pin connectors, micro-screws, springs, IC sockets, micro-gears and micro-shafts has increased significantly due to the downsizing of products as reported by Engel and Eckstein, Su et al., and Liu et al. [13-15]. The fact that material properties change with specimen sizes has been well-known for several years as mentioned by researchers Neugebauer, and Doerner et al. [16, 17].

Miniaturisation technology is now crucial in the fabrication of micro parts. When the size of a material is decreased to micro-scale, changes occur in its mechanical behaviour and such effects are called size effects as reported by Chan et al. [18]. Size effect is characterised by grain size, dimension of the specimen and size of the surface topography. Materials demonstrate mechanical properties such as modulus of elasticity, tensile strength, elongation, hardness and fatigue limit [19-22], and present their elastic and non-elastic behaviour when a certain force is applied. This indicates the suitability of a material to certain mechanical applications [23-25]. The tensile test is a method used to evaluate the structural response of steel to applied force with the result expressed as a relationship between stress and strain. The current study follows several previous researches that had dealt with macroscopic and microscopic behaviour and fatigue properties of pre-hardened austenitic stainless steel [26-29]. Plastic deformation during forming can lead to deformation-induced transformation from the original ductile austenite phase to a stronger martensite [30-33]. In general, the formation of martensite depends on chemical composition, temperature, stress state, strain and strain rate [34-36]. The influence the strain rate has on mechanical properties of 304 stainless steels has also been reported by Refs.[37-42]. Over the last four decades, the thickness of car bodies has reduced significantly from 1.5 mm to less than 0.5 mm. This is mainly due to the need for lighter cars to save fuel costs [43-45]. The high strength of a car body can be maintained using a newly developed thin steel sheet. However, the mechanical properties of materials are usually tested using a standard large sample, thus do not necessarily represent thin or small components' properties. This is the driving factor behind many studies surrounding the mechanical properties of micro-sized specimens used in the production of tiny metal-based components. In this study, the effect of tensile strain on the mechanical properties (i.e., hardness, tensile behaviour and fatigue strength) of a very thin 304 stainless steel sheet was investigated. The results were then compared to the fatigue strength of hardened 304 stainless steel.

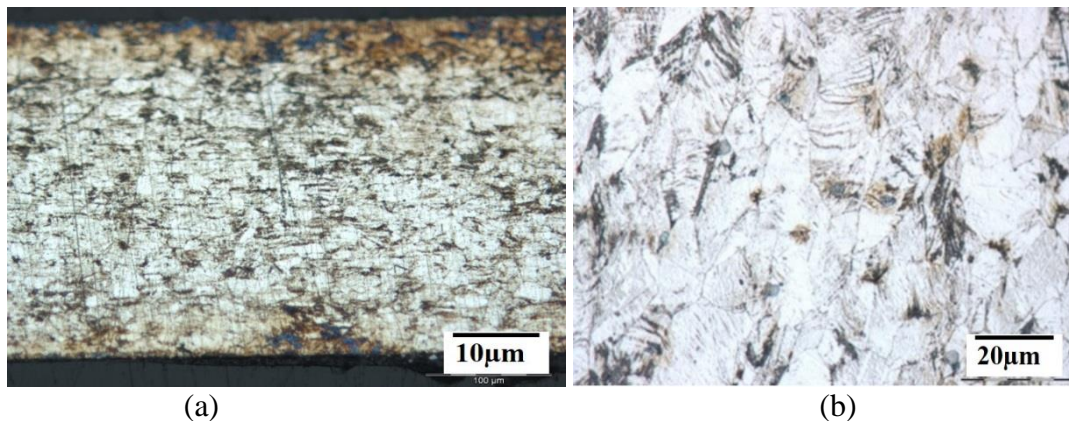
METHODS AND MATERIALS

Experimental Procedures

This study used a very thin 304 stainless steel sheet with a thickness of 300µm. The chemical composition of the material (wt. %) is listed in Table 1. As shown in Figure 1, experimental samples were machined from 300µm sheets into dumbbell-shapes using an Electrical Discharge Machining (EDM) wire cutter according to ASTM E8 [46]. The width and length of gauge area were 5 mm and 28 mm, respectively. Vickers hardness was implemented using the Zwick Roell Indentec micro-hardness tester according to ASTM E384 [47]. The hardness test was conducted on the surface sample with a 100g load indenter and a dwell time of 15 seconds. The test was carried out ten times for each sample at different location points for two different cases: first, for the as-received material and second, for heat-treated material. The final Vickers hardness result was expressed as an average of the two. All the samples were annealed at 700⁰C to relieve the stress caused by the cold and EDM cutting process. Several tests were conducted to estimate the hardness, tensile strength and strain process of 2% and 5% of the annealed samples. The fatigue strength was then compared to that obtained by Bomidi et al. [48] for hardened 304 stainless steel according to ASTM E468 [49].

Table 1. Chemical composition (wt.%).

C	Mn	F	S	Si	Cr	Ni
0.08	2.00	0.045	0.03	1.0	18.0-20.0	8.0-11.0

Figure 1. Tensile specimen size and configuration (units in mm), thickness is 300 μ m.Figure 2. Microstructures of 304 stainless steel sheet with a thickness of 300 μ m (a) not annealed (b) after being annealed.

The tensile test was performed using a Zwick Roell Z100 universal testing machine of 100kN capacity. Three samples (as-received and heat-treated) were used. These samples were labelled 1, 2 and 3 and were ground using emery papers, polished using buff clothes with 1 μ m diamond suspension, before being etched to reveal the microstructure. The microstructures of 300 μ m thickness 304 stainless steel thin sheets without annealing are shown in Figure 2(a), and those after being annealed are shown in Figure 2(b). The grain size of the samples was about 20-25 μ m. All fractured surfaces of tensile and fatigue samples were then observed using Scanning Electron Microscopy (SEM). Broken specimens after the tensile and fatigue tests were fixed to a jig before put in a vacuum chamber for SEM observation. The SEM used was the EVO series by Zeiss. 15 kv was used for the imaging of the fractured surface.

RESULTS AND DISCUSSION

Vickers Hardness Test

Hardness testing is very useful for the quality control of manufacturing processes, evaluation of materials, and for research and development purposes. Although hardness

is empirical in nature, it is also an indication of ductility. Hardness may also correlate to tensile strength in many metals. In this study, the Vickers hardness test was conducted on the sample surface with a load indenture of 100g and a dwell time of 15 seconds, according to ASTM E384 [47]. The test was carried out on two different cases: first, for the as-received material, which exhibited an average Vickers hardness of 387; and second, for the heat-treated material, which exhibited an average Vickers hardness of 357 (Figure 3). The reduced hardness in the heat-treated samples could have been contributed by the stress released and softening caused by the heat treatment process. This is because the recrystallization of the ferrite structure causes a reduction of carbon (due to diffusion), increases ductility and reduces hardness as reported by Mudashiru and Adio [50]. However, the samples' hardness decreased with increasing tempering temperature as mentioned by some researchers such as Fadare et al., Shrestha et al., and Ismail et al. [51-53].

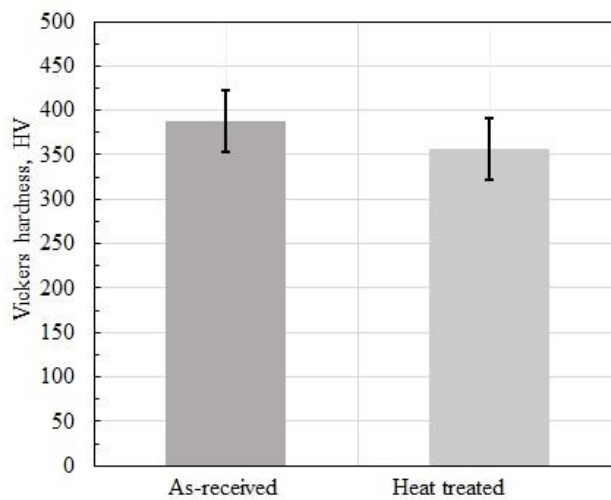


Figure 3. Micro Vickers hardness of 300 μ m thickness 304 stainless steel thin sheet for as-received and heat-treated specimens.

Tensile Properties

The stress-strain curves for the 300 μ m thickness 304 stainless steel sheets are shown in Figure 4. A summary of the tensile properties is listed in Table 2. Three samples were tested from the as-received and heat-treated specimens. These samples were labelled 1, 2 and 3 for each condition. The physical behaviour of the specimens was observed from its initial loading until specimen failure same as reported by Al-Bakri et al. [54]. Initially, both samples under the different conditions were loaded in the elastic range until they reached their respective elastic limits. Thereafter, both samples behaved differently. The heat-treated specimens exhibited a smoother stress-strain curve from the proportional limit to the ultimate stress level compared to the as-received specimens (Figure 4). For the non-heated specimens, the yield stress was evaluated based on the load at 0.2% strain. The ultimate tensile strength was found at 1240 MPa. Beyond the maximum point, the stress gradually decreased and the specimens failed at about 42% strain. However, this yield point (786 MPa) was much lower than the 0.2% yield stress of the non-heated specimens (893MPa). The upper yield point in heat-treated specimens was followed by a sudden reduction in stress to the lower yield point. At this stage, the specimens continued

to elongate without a significant change in their stress level for up to about 5% strain. The load increment was resulted in increasing strain values.

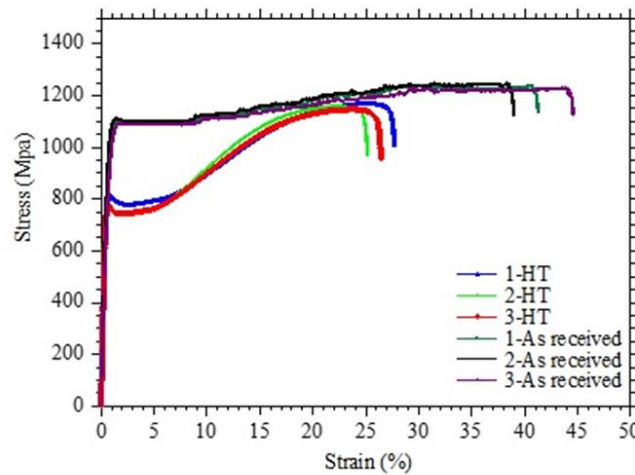


Figure 4. Stress-strain curves of 300µm thickness 304 stainless steel sheets for as-received and heat-treated specimens.

Table 2. Tensile properties of 300µm thickness 304 stainless steel sheets for as-received and heat-treated specimens.

	E (GPa)	σ_y (MPa)	σ_{UTS} (MPa)	El. (%)
As received	171	893	1240	42
HT	209	786	1160	26

After the annealing treatment, the room temperature yield stress of the 300µm heat-treated specimens decreased from 893MPa to 786MPa, the ultimate strength decreased from 1240MPa to 1160MPa, and the tensile elongation decreased from 42% to 26% compared to the as-received specimens as mentioned by Wang et al. [55]. These results were similar to those reported by Wang et al. [55]. The Young’s modulus values were 209 GPa and 171GPa for the heat-treated and as-received specimens respectively (Table 2). After the heat treatment, the material softened and the stress due to manufacturing process, i.e. rolling process, was released. Therefore, the tensile yielding and hardness reduced are as shown in Figures 3 and 4. The heat treatment caused the increase in the work hardening rate, but also resulted in the reduction of tensile elongation.

Fatigue Strength Test

The S-N curves compare the fatigue strengths of 304 stainless steel sheets under heat treatment and strained to 0%, 2% and 5% samples with those after hardening by [48] as shown in Figure 5. The samples subjected to 5% strain had a higher fatigue life than the samples subjected to 2% strain, 0% strain and the hardened 304 stainless steel. Samples with 5% strain showed the highest endurance limit (675MPa) at 10^7 cycles, followed by 2% strain samples (650MPa) and 0% strain samples (600MPa). The endurance limit for hardened samples was the lowest at 585MPa. This difference proves that higher strain values lengthen the fatigue life cycles and endurance limit of 304 stainless steel due to

both work-hardening and strain-induced martensitic transformation. This further proves that the process of inducing the 5% strain was successful in improving fatigue strength. This is because the straining process induced a large amount of dislocations, resulting in increased tensile strength and better balance between hardness and ductility as mentioned by Nakajima et al. and Uematsu et al. [56, 57]. The straining process had a positive impact on the sample by delaying the generation and propagation of fatigue cracks. The crack propagation could have also been delayed by the hardened element as reported by Nakajima et al. and Nakajima et al. [58, 59]. Furthermore, the straining process provided high fatigue resistance to the material before the material finally failed.

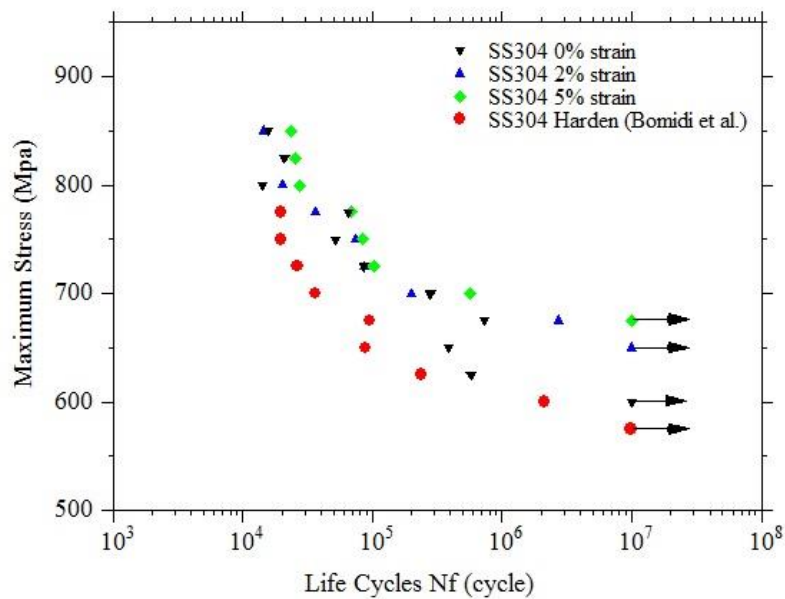


Figure 5. Comparison of S-N curves of SS304 heat treated and strained 0%, 2% and 5% samples, and hardened SS304 [48].

Fracture Behaviour Analysis

Fracture Behaviour for Tensile Test

The fractured surface was observed using a Scanning Electron Microscope (SEM) for the as-received and heat-treated 304 stainless steel sheet samples of 300µm thickness. The observations were made after the tensile tests were conducted to analyse the failure processes as shown in Figures 7 and 8. Figure 7 clearly shows small tensile dimples, cleavage and voids on the fractured surfaces of the specimens. The void seems to be less significant in becoming a fatigue crack initiation site compared to the damage induced by the localized dislocation and slip of persistent slip bands. Figure 8 shows a general phenomenon of significant necking. A reduction in thickness direction can be seen in Figure 8(a). Magnified observation shows small tearing with some dimples on the fractured surface of the sample as seen in Figure 8(b). However, the fractured surfaces of the heat-treated samples appear to be rougher with an apparent tear pattern associated with the dimples. This is because martensite fraction has a major influence on void nucleation and growth as reported by Chen et al. [60]. Figure 6 shows the fractured shape of the samples.

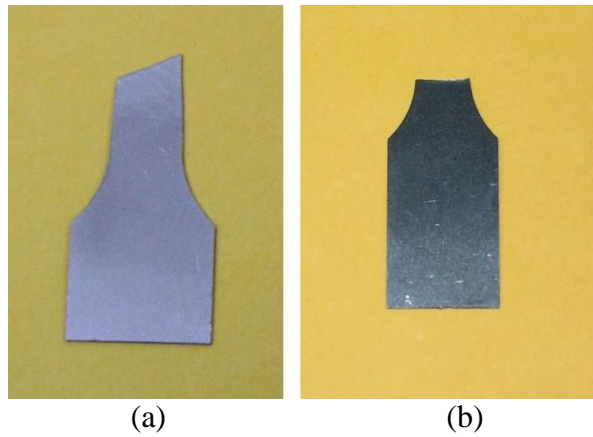


Figure 6. Fracture shape of samples (a) tensile (b) fatigue.

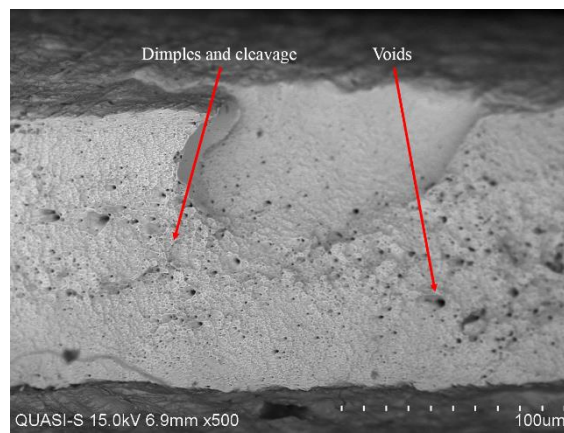


Figure 7. SEM fracture surface of as-received tensile specimens of 304 stainless steel sheet with 300µm thickness (500X magnification).

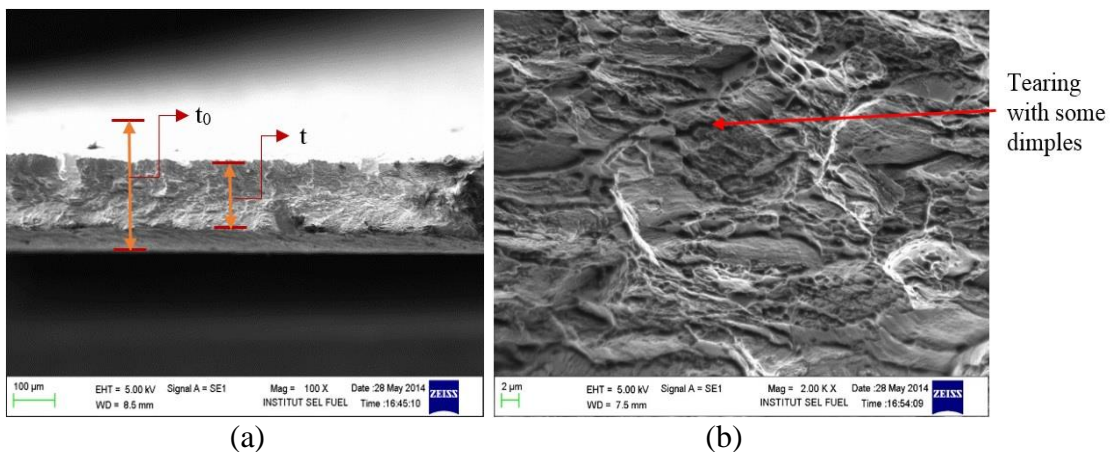


Figure 8. SEM fracture surface of heat treated tensile specimens of 304 stainless steel sheet with 300µm thickness with (a) 100 X magnification, t_0 = specimen thickness before tensile test and t = specimen thickness after tensile test and (b) 2000 X magnification.

Fracture Behaviour for Fatigue Test

There were some differences in the fracture behaviour of the samples with 2% strain and that with the 5% strain. These differences can be seen in Figure 9. It shows the strain on

the 304 stainless steel sample when subjected to fatigue crack propagation area; the area is seen to shrink rapidly with growing cracks. The resulting surface is curved and undulated. This is because the strain had caused an increase in the density of dislocations and slips on the plane of the material microstructure as reported by Chen et al. and Shintani and Murata [60, 61]. The increase in both of these cases resulted in micro-cracks which further led to the generation of cracks. As the crack propagation process began, micro-cracks started connecting and caused faster crack propagation, thereby lowering the fatigue life of the material. In addition, samples that were subjected to 2% and 5% strains also showed a difference in their fractured surfaces. Samples subjected to the 5% strain had a smaller fatigue crack propagation area than the samples subjected to the 2% strain. This happened because in the case of the sample with the 5% strain, the value of the stresses became greater than the stress applied to the 2% strain. This increased the density of dislocations and slip planes, thereby contributing to the occurrence of micro-cracks larger than those caused to the 2% strain as mentioned by Chen et al. and Shintani and Murata [60, 61]. These micro-cracks had led to the process of crack generation and rapid crack propagation.

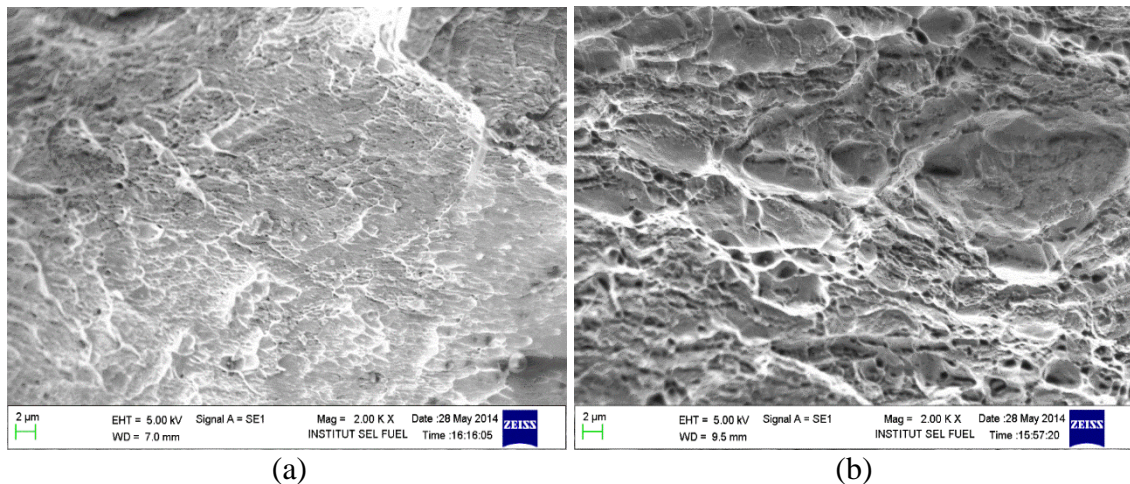


Figure 9. SEM of fractured surface of 304 stainless steel sheet fatigue test specimens at 300 μ m thickness with (a) 2% strain and (b) 5% strain.

CONCLUSIONS

The conclusions obtained from experimentation on the fatigue properties of strained 304 stainless steel materials can be summarized as follows;

Heat treatment on the mechanical properties of the 304 stainless steel had influenced the 300 μ m samples. All samples showed differences in their Young's modulus, yield stress, ultimate tensile strength, elongation and hardness values. However, the 300 μ m samples showed its highest ductility in both heat-treated and non-heat treated conditions. Furthermore, the as-received samples exhibited higher ultimate tensile strength compared to that shown by the heat-treated samples. Meanwhile, the heat-treated specimens exhibited a smooth stress-strain curve from the proportional limit to the ultimate stress level compared to the stress-strain curve of the as-received specimens.

The fatigue test showed that the specimen with a higher strain value of 5% lengthened the fatigue life cycle more than by the 2% strained, 304 stainless steel and by the 0% strained, hardened 304 stainless steel. However, the fracture behaviour for tensile test showed small tension dimples, cleavage and voids on the fractured surfaces of the as-

received specimens. There was a clear reduction in the thickness direction of the heat-treated specimens (lower magnification) for the tensile tested samples. The fractured surfaces of the heat-treated specimens turned out to be rougher (on higher magnification) owing to the presence of a tearing pattern associated with the dimples.

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