Increasing the strength of AISI 430 ferritic stainless steel by static strain ageing

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Abstract

In this study, the strain ageing behaviour of AISI 430 ferritic stainless steel is investigated. A certain part of the as-received ferritic stainless steel test pieces was pre-strained for 5 % in tension, then aged at 100, 200, 300, and 400 °C for 30 min in a furnace. The other part was solution heat-treated at 950 °C for 15 minutes, water quenched and pre-strained for 2 or 5 % in tension, then aged at 100, 200, 300, and 400 °C for 30 min. UTS (ultimate tensile strength), ΔY (increase in yield strength due to strain ageing), percentage elongation and yield point elongation measurements were employed to investigate the effect of strain ageing on the mechanical properties. The experimental work has revealed that different ageing temperatures significantly affect the mechanical properties of the AISI 430 ferritic stainless steel.

Key words: ferritic stainless steels, strain ageing, tension test

1. Introduction

Ferritic stainless steels are (11–30 %) chromium and fewer amounts of carbon, nitrogen and nickel containing alloys. They are noted for their stress-corrosion cracking (SCC) resistance and good resistance to pitting and crevice corrosion in chloride environments in many applications [1, 2]. They may have good ductility and formability, but high-temperature mechanical properties are relatively inferior to the austenitic stainless steels. Problems such as loss of ductility and toughness when exposed to elevated temperatures, occurring in these steels, for instance, during welding, are being dealt in [2, 3] and the main challenge now is to explore attractive, non-conventional properties that the material might exhibit, in order to offer alternative choices for engineering design [4].

The kinetics of ageing in ordinary ferritic steels is, accordingly, governed by the diffusion of interstitial solute atoms (as little as 0.003 % carbon or nitrogen) towards mobile dislocations. The decrease in lattice strain energy resulting from the formation of clouds of these atoms around dislocations, the so-called Cottrell atmospheres, is the driving force responsible for strain ageing in ferritic steels [4]. The main effects of strain ageing on the mechanical properties are thus the increase in the yield and ultimate tensile stresses and a decrease in ductility [4, 5]. It is demonstrated that the rate at which these changes occur at a given ageing temperature is a function of the interstitial solute content. The concentration of interstitial solute atoms in solid solution must be reduced to about 0.0001 % (1 ppm) or less to eliminate the effects of strain ageing. Strain ageing effects can approach their maxima at concentrations of only about 0.002 % [6, 7]. In low carbon steels, the phenomenology, kinetics and atomic mechanisms of strain ageing are well understood [4]. For instance, the bake hardenable steels and dual phase steel, in which controlled ageing is employed to harden deep drawn car panels after final mechanical processing [8], are an example of what can be achieved when such characteristics of strain ageing are known in detail.

As relatively inconclusive work is available in the literature, an effort is needed to study the effect of pre-strain, ageing temperature of as-received and solution heat-treated commercial AISI 430 grade ferritic stainless steel on mechanical properties. This was the idea underlying the present work, in which the phenomenology and kinetics of strain ageing in as-received

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and solution heat-treated commercial AISI 430 grade steel were characterized by means of tensile tests. The paper focused mainly on examining the changes in UTS (ultimate tensile strength), ΔY (increase in yield strength due to strain ageing), percentage elongation, yield point elongation of steel when heat treated at different ageing temperatures for 30 minutes.

2. Experimental method and materials

The steel used in this investigation was a commercial grade of AISI 430, received as a sheet with a thickness of 1.2 mm. Its chemical composition is 0.045 % C, 18.16 % Cr, 0.60 % Mn, 0.177 % Ni, 0.396 % Si, 0.066 % Cu, 0.015 % P, 0.001 % S, 0.003 % Ti, and 80.33 % Fe (wt.%). All the tensile test specimens (60 mm gauge length by 12 mm gauge section) were pressed from the as-received ferritic stainless steel sheet. In order to preserve the supersaturated solid solution at room temperature, the AISI 430 grade steel test pieces were soaked in a furnace for 15 minutes at 950 ± 2 ℃ followed by quenching in water at room temperature. This process is known as solution heat treatment. After solution heat treatment, all the ferritic stainless steel test pieces were kept in a freezer. This is very important to avoid the natural ageing of the alloy at room temperature.

While solution heat-treated test pieces were prestrained for 2 or 5 % in tension shortly after the solution treatment, as-received test pieces were only pre-strained for 5 % for the sake of comparison. The amount of pre-strain to which each specimen was subjected was measured by extensometer. After the process of solution heat treatment and pre-straining, the test pieces were artificially age hardened at 100, 200, 300, and 400 ℃ for a period of 30 min in a furnace and subsequently cooled in air. Finally, they were tested in tension at room temperature using a Schimadzu tensile testing machine at a crosshead speed of 2 mm min^{-1}. Triplicate samples were employed per run in order to correct minor differences in experimental conditions. The increase in yield stress ΔY due to ageing is defined as $(\sigma_y - \sigma_f)$, the difference between σ_y, the lower yield stress after ageing, and σ_f, the flow stress at the end of the pre-straining.

The fractured surfaces of aged test pieces were also analysed using Scanning Electron Microscope (SEM).

3. Results and discussion

Figures 1 and 2 show UTS and ΔY values of as-received and solution heat-treated test specimens aged at 100, 200, 300, and 400 ℃ for 30 min after prestraining in the range studied. It can be seen, as the ageing temperature increases for the ageing time of

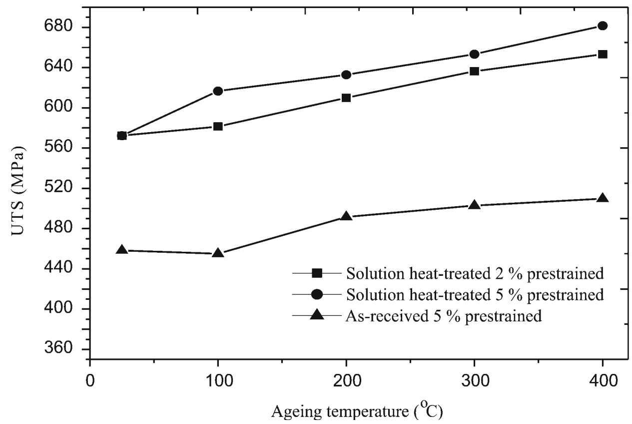


Fig. 1. Ultimate tensile strength of test samples.

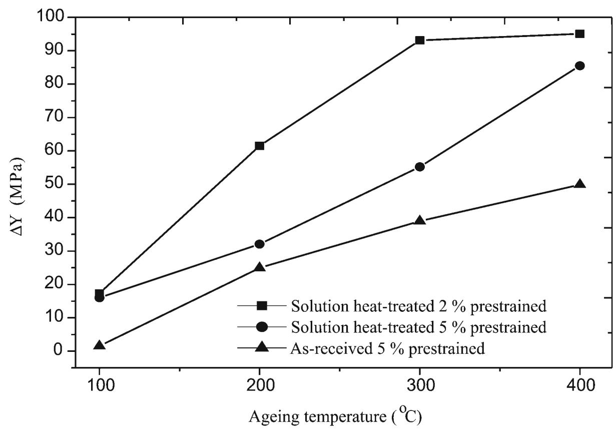


Fig. 2. ΔY values of test samples.

30 min, a continuous increase in tensile strength and ΔY is noticed. Maximum tensile strength and ΔY are observed when the alloy is aged at 400 ℃ for 30 min. For example, solution heat-treated test pieces showed the highest ΔY value of 95.1 MPa and 85.52 MPa after pre-straining by 2 % and 5 %, respectively. However, as-received test pieces showed the lowest ΔY value of 49 MPa after 5 % pre-straining and ageing at 400 ℃ for 30 minutes. An increase in the ΔY values of as-received and solution heat-treated test pieces is the strongest evidence of strain ageing that is present in AISI 430 grade steel.

It is very clear from the foregoing discussion that solution heat-treated test pieces showed a decrease in ΔY as the amount of tensile pre-strain was raised from 2 to 5 % for the ageing temperatures in the range studied. The mechanism responsible for decreasing ΔY with increasing pre-strain has not been widely discussed in the literature. Lee and Zuideman [9] suggest that the effect is due to stress relaxation in the strain fields of dislocations during ageing. On the other hand,

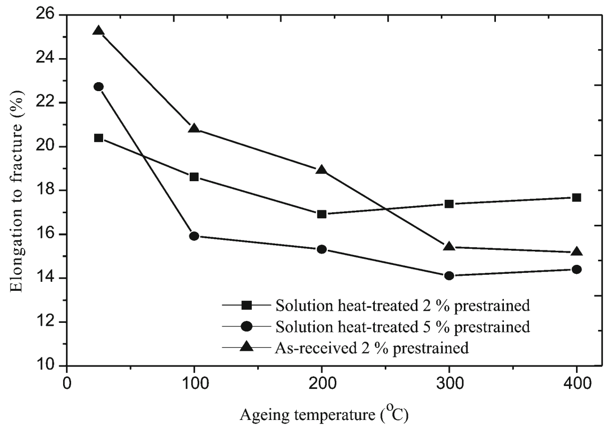


Fig. 3. Elongation to fracture values versus ageing temperature for test samples.

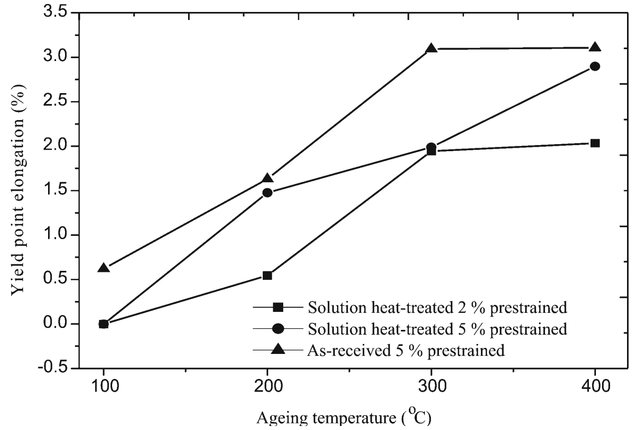


Fig. 4. Yield point elongation values versus ageing temperature for test samples.

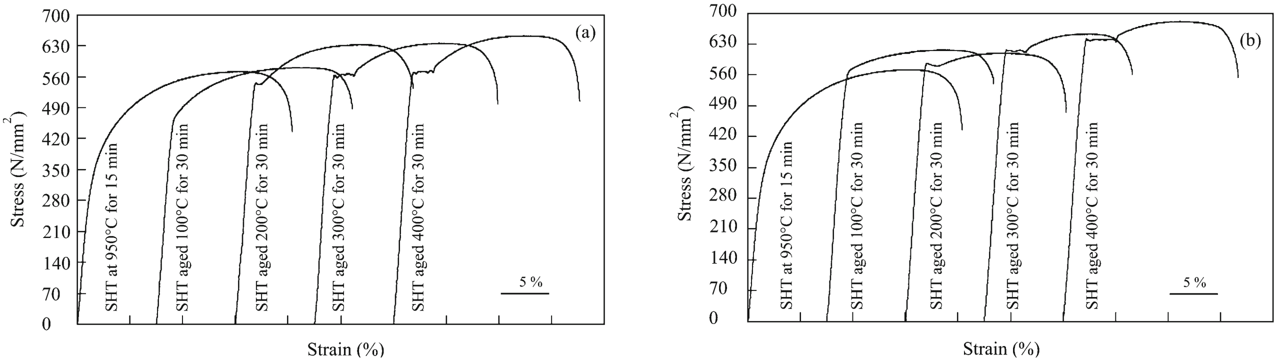
according to some other investigators [10, 11], it is due to the fact that if pre-strain increases, the dislocation density becomes higher and, consequently, the amount of carbon per dislocation decreases, leading to the decrease in ΔY. However, it was found that increasing pre-strain from 2 to 5 % markedly increased the UTS of solution heat-treated test pieces after all ageing temperatures used in this study (see Fig. 1). Palček and Fogelton [12] investigated the influence of the ageing and plastic deformation on temperature dependence of internal friction of low carbon ferritic steel. They observed that the plastic deformation caused an increase of the dislocation-enhanced Snoek maximum (DESE). The results obtained from the present investigation therefore support a conclusion that the rate of decrease in ΔY is rather insensitive to dislocation density and is principally dependent on the solute segregation per dislocation. Similar results were obtained by Gündüz [13] who showed that increasing pre-strain from 2 to 4 or 6 % markedly increased the UTS but decreased ΔY values of dual phase carbon steel.

It is seen from Figs. 3 and 4 that both as-received and solution heat-treated test pieces showed an increase in yield point elongation, however percentage elongation decreased as the ageing temperature was raised. For example, as-received test pieces showed the lowest percentage elongation (15.18 %) after pre-straining by 5 % and ageing at 400 ℃ for 30 min. Solution heat-treated test pieces showed the lowest percentage elongation (16.92 %) at 200 ℃ and 14.11 % at 300 ℃ after pre-straining by 2 % and 5 %, respectively. The loss of ductility can be attributed to the ageing and the precipitation of intermetallic phases, because many of these alloys are subject to the precipitation of undesirable intermetallic phases when exposed to certain temperature ranges 370–480 ℃. It was reported that the precipitation of alpha prime and Cr-rich phases such as $M_{23}C_6$, $M_{23}(C,N)_6$ carbides or Cr-rich nitrides occurred between 370 and 480 ℃, so the overall toughness reduced. The combined effect of these precipitates results in 475 ℃ embrittlement [14].

The change in yield stress is the most consistent indication of strain ageing at all solute contents and at all ageing times. The ultimate tensile strength and elongation only change at later stages of ageing when high solute contents are present; the yield point elongation increases rather irregularly. It is believed that static strain ageing causes the plateau in the engineering stress versus strain plot due to higher concentration of solute atoms in atmosphere at dislocations in α-iron at high temperatures.

Four distinct stages in strain ageing can be identified in low carbon commercial steel after ageing at 60 ℃ for various times. In stage 1, the yield stress and the Luders strain or yield point elongation rise but other properties remain unaltered. In stage 2, the yield stress continues to rise, the Luders strain remains roughly constant and the flow stress beyond the Luders strain raises but with an unaltered rate of strain hardening. Stage 3 is similar to stage 2 except that the strain hardening rate increases, with a resultant increase of UTS and decrease in elongation. Stages 2 and 3 are referred to as strain-age-hardening since they reflect permanent hardening rather than a purely yield-point effect as in stage 1. In stage 4, overageing effects lead to softening, although the Luders strain is maintained and often even rises in the fine grained material [7, 15].

An increase in tensile strength and ΔY but a decrease in percentage elongation can be explained by diffusion-assisted mechanism, and also by hindrance of dislocation by impurity atoms, i.e. foreign particle of second phase, since the material after quenching from 950 ℃ (solution heat treatment) will have excessive vacancy concentration. The strengthening effect of



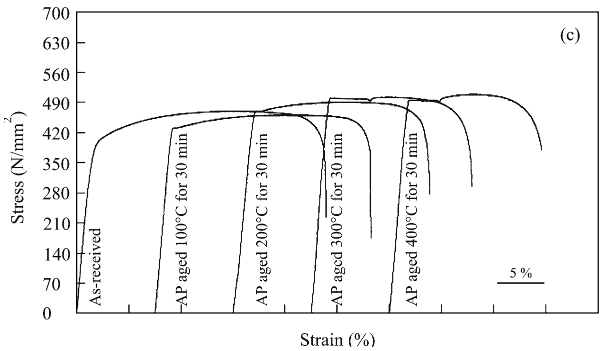


Fig. 5. The stress-strain diagrams of solution heat-treated test pieces pre-strained in tension by 2 % (a), 5 % (b) and as-received test pieces (c) pre-strained in tension by 5 % and then aged at 100 °C, 200 °C, 300 °C, and 400 °C for 30 minutes.

AISI 430 grade steel could also be explained as a result of interference with the motion of dislocation due to the presence of foreign particle of any other phase. Buono et al. [4] measured the electrical resistivity of the AISI 430 steel aged at different temperatures for different ageing times. According to their results, the migration of carbon atoms from solid solution to dislocations in ferrite would lead to changes in electrical resistivity of the order of -1.5×10^{-3} μΩ cm ppm^{-1} in weight of carbon. They also indicated that there was a continuous decrease in electrical conductivity in test pieces with increasing ageing time and temperature because of the degree of irregularity in the lattices [4].

Figures 5a,b show stress-strain diagrams of the solution heat-treated test pieces pre-strained in tension by 2 and 5 %, respectively, aged at different temperatures and restrained. Figure 5c also shows stress-strain diagram of as-received test pieces pre-strained by 5 %, aged at temperatures in the range studied. As can be seen, as-received test pieces have rounded stress-strain curves prior to any ageing. According to TEM observations which were carried out by Sotomayor and Herrera [16], this seems to be due to submicroscopic precipitation of low-carbon carbonitrides – most probably Cr_2(C,N) – preferably on grain boundaries. The locking of interstitials (N, C) by these precipitates could explain the absence of discontinuous yielding. When the solution heat-treated test pieces were quenched in water after soaking in a furnace for 15 min at 950 °C, most of the carbon and/or nitrogen stayed in solid solution due to higher cooling rate. Gündüz and Cochrane [17] showed that the higher cooling rate such as air cooling was not sufficiently slow to allow full precipitation of all carbides; this indicates presence of carbon and/or nitrogen in solid solution. However, solution heat-treated test pieces showed continuous yielding behaviour prior to any ageing, although they probably contained more carbon and/or nitrogen in solid solution than as-received test pieces after quenching in water. This is due to greater activation energy for strain ageing in this class of steels. Buona et al. [4] calculated the activation energy as $AH = 126.7$ kJ mol^{-1} for strain ageing in AISI 430 stainless steel. This value is considerably greater than the activation energy usually found for strain ageing in low carbon steels, which is equal to the activation energy for the diffusion of C atoms in ferrite, 84.2 kJ mol^{-1}. However, it is possible that the affinity of chromium for carbon atoms modifies the activation energy for diffusion of the latter in AISI 430 steels to such an extent. Therefore, solution heat-treated test pieces did not show any discontinuous yielding behaviour, because chromium retards the diffusion of carbon to dislocations at room temperatures in AISI 430 grade stainless steel.

When the as-received and solution heat-treated test pieces were pre-strained in tension by 2 or 5 % and aged at 100, 200, 300, and 400 °C, they showed discontinuous yielding behaviour and developed yield plateaus. This is due to concentration of solute atoms in atmosphere at dislocations in α-iron at high temperatures. Buona et al. reported that dislocations in these steels tended to be arranged in a cellular

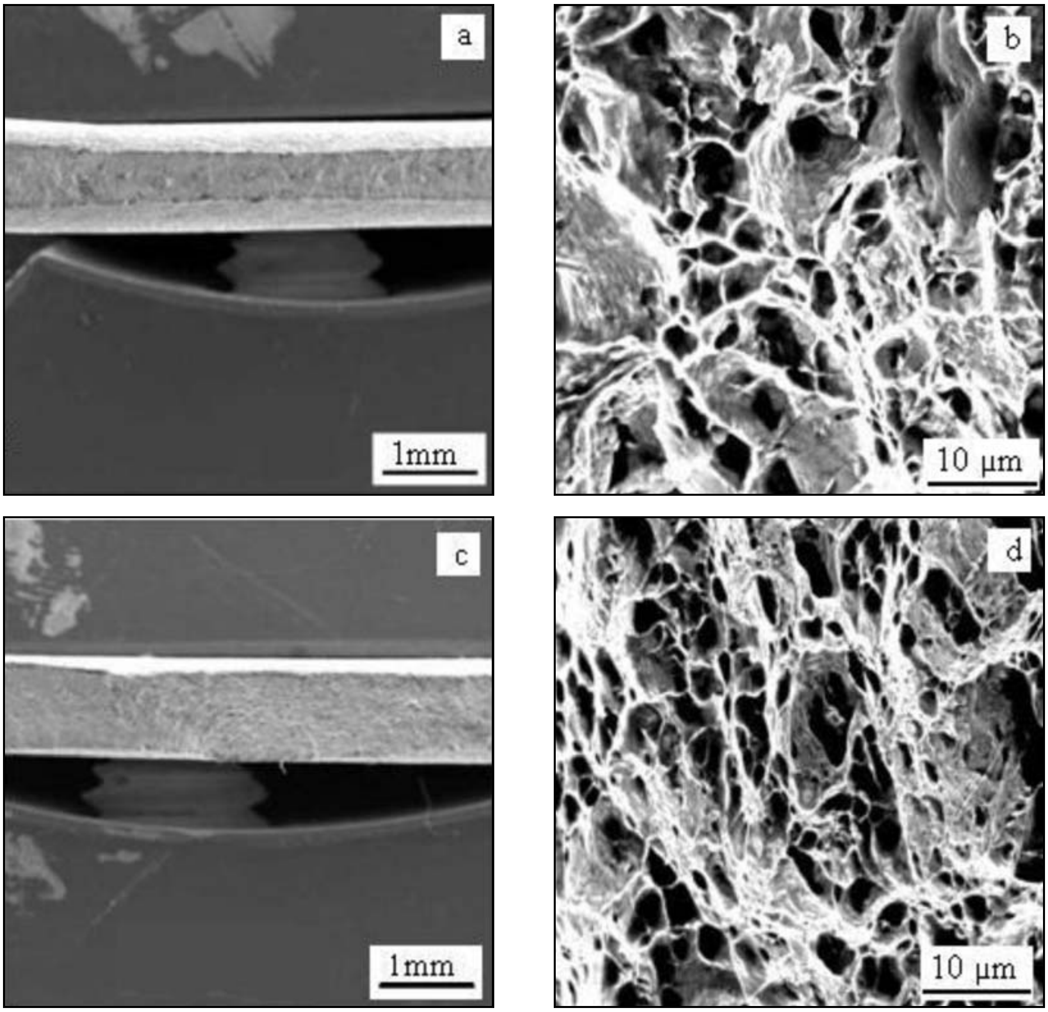


Fig. 6. The fracture surface of the as-received (a, b) and the solution heat-treated (c, d) AISI 430 grade steel.

structure [4]. It is thought that clustering carbon and nitrogen atoms prevent the movement of dislocations at the ageing temperatures of 100–300 ℃. However, the similar job may be done by precipitation of Cr-rich carbides or nitrides when the ageing temperature approaches 400 ℃. Ferrante et al. [18] observed intensive precipitation of 0.5–1.0 μm long platelets identified as Fe-Cr-Mo carbonitrides in the ferritic grains of AISI 2205 duplex stainless steel in the as-welded state and after ageing at 380 ℃. These features were homogeneously dispersed in the central part of the ferritic grains and heterogeneously arranged along curved lines, the latter being possibly associated with previous ferritic or austenite/ferrite grain boundaries.

It is also seen in Fig. 5 that the strength properties increase with the ageing temperature indicating that strain ageing is a possible hardening mechanism for this class of steel. In addition, solution heat-treated test pieces pre-strained in tension by 2 or 5 % after ageing at different temperatures showed slightly higher strength properties than as-received test pieces pre-strained in tension by 5 % for all ageing temperatures. For example, ultimate tensile strength of as-received AISI 430 grade steel increased approximately to 100 MPa after solution heat treatment at the temperature of 950 ℃ for 15 minutes and quenching in water prior to any ageing. It can be attributed to the solution heat treatment in which too much free carbon and/or nitrogen atoms are enclosed in solid solution or in precipitates of Cr-rich phases, so they interact with dislocations and prevent their movement.

The fracture surface of as-received and solution heat-treated test pieces are shown in Fig. 6 prior to any pre-strain and ageing. As can be seen the as-received and solution heat-treated AISI 430 grade steel showed certain surface roughness typical of ductile fracture and microscopically a surface covered by dimples of several sizes. However, the solution heat-treated AISI 430 grade steel showed lower decrease in area due to strain ageing which results in the interaction between dislocations and solute atoms or precipitate particles. The lower reduction in area of solution heat-treated test pieces could also be attributed

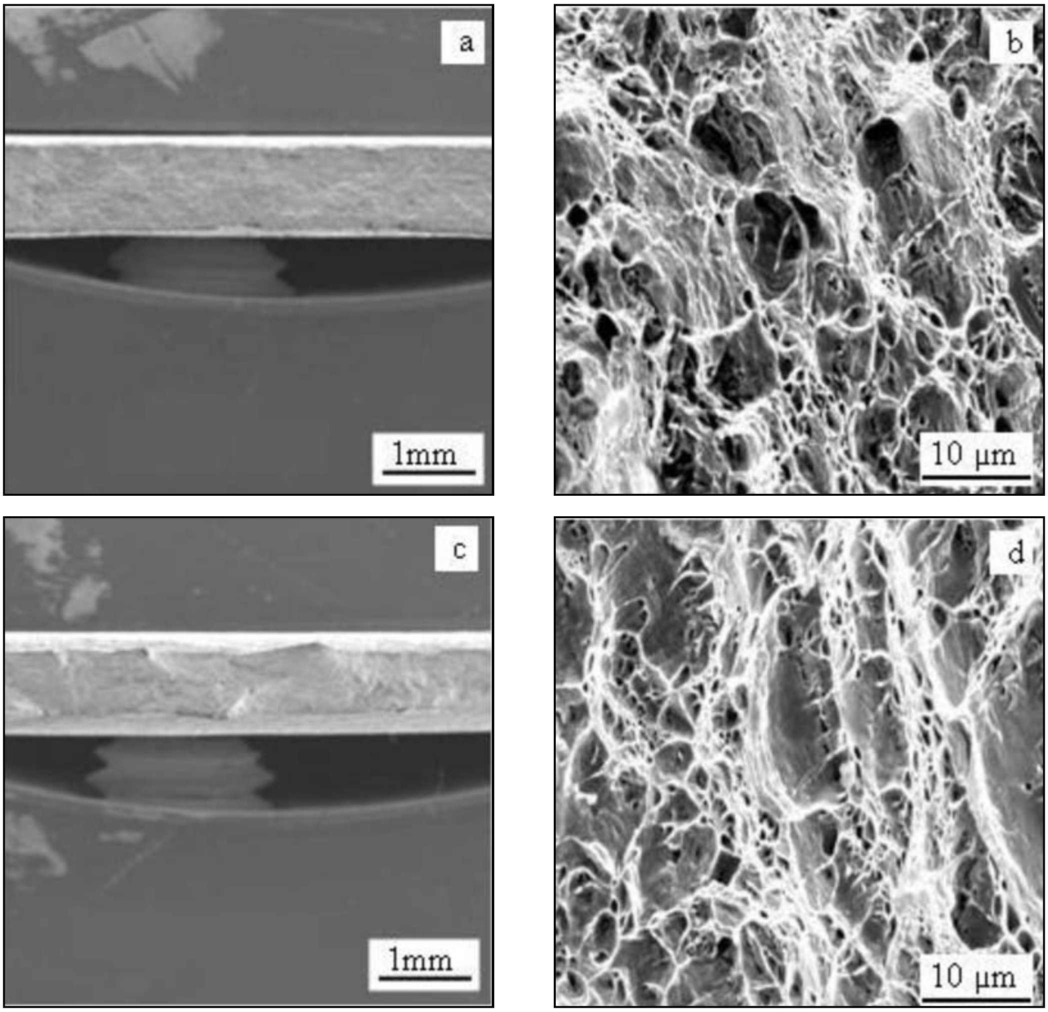


Fig. 7. The fracture surface of the solution heat-treated test pieces pre-strained in tension by 5 % and then aged at 100 ℃ (a, b) and 400 ℃ (c, d).

to the high temperature embrittlement which is influenced by composition, particularly chromium, interstitial concentration, and grain size [19]. Krafft [14] also reported that the Cr-Fe ferritic alloys react to form Cr carbide precipitates at the grain boundaries and within the grains when heated to 315–925 ℃.

Figure 7 also shows fracture surfaces of solution heat-treated test pieces pre-strained in tension by 5 % and then aged at 100 and 400 ℃. As seen in Fig. 7, solution heat-treated test pieces pre-strained in tension by 5 % and then aged at 100 and 400 ℃ showed transcrystalline character with the dimple morphology. However the dimple size of test pieces decreases with increasing ageing temperature to 400 ℃. The reason of this behaviour is the coalescence of dislocations, increasing the development of high angle boundaries at which cavity formation proceeds. Consecutive stages of the ductile fracture formation, namely growth and coalescence of voids, are accomplished by the usual mechanisms as suggested by Besterci et al. [20]. Dislocation coalescence manifested by the increasing ageing temperature to 400 ℃ affects the fracture initiation.

As a conclusion, a significant increase in mechanical properties is observed in AISI 430 grade steel, after 30 min of ageing times at temperatures 100, 200, 300, and 400 ℃, indicating that, if appropriately controlled, strain ageing might be used as a hardening mechanism for this class of steel.

4. Conclusions

In this work, the artificial ageing behaviour of AISI 430 grade ferritic stainless steel was investigated under as-received and solution heat-treated conditions. The conclusions derived from this study can be given as follows:

– An increase in the ultimate tensile strength and ΔY, but a decrease in percentage elongation of as-received and solution heat-treated AISI 430 grade steel with increasing in ageing temperature for 30 min can be explained by a diffusion assisted mechanism which causes distortion of lattice planes and hindering of dislocation movement by the impurity atoms. The strengthening effect can also be a result of interference with the motion of dislocation, due to the formation of precipitates. This indicates that strain ageing is a possible hardening mechanism for this class of steel.

– Solution heat-treated test pieces pre-strained in tension by 2 or 5 % showed slightly higher strength properties than as-received test pieces pre-strained in tension by 5 % for all ageing temperatures. This is due to solution heat treatment in which too much free carbon and nitrogen atoms are enclosed in solid solution, so they interact with dislocation. This is also due to pre-straining prior to artificial ageing which enhances the competitive precipitation kinetics of the precipitate in the matrix. Matrix precipitation of this more abundant and finer strengthening phase directly correlates to the increased strength.

– Solution heat-treated test pieces showed a decrease in ΔY as the value of tensile pre-strain raised from 2 to 5 % for the ageing temperatures in the range studied. However, it was found that increasing pre-strain from 2 to 5 % markedly increased the UTS of solution heat-treated test pieces after all ageing temperatures used in this study. This indicates that the rate of decrease in ΔY is rather insensitive to dislocation density and is principally dependent on the solute segregation per dislocation.

– As-received test pieces have rounded stress-strain curves prior to any ageing due to submicroscopic precipitation of low-carbon carbonitrides – most probably $Cr_2(C,N)$. Solution heat-treated test pieces also showed continuous yielding behaviour prior to any ageing, although they contained more carbon and/or nitrogen in solid solution due to higher cooling rate. This indicates that chromium in solid solution retards the diffusion of carbon in AISI 430 grade stainless steel.

– Fractographic analysis showed that both as-received and solution heat-treated test pieces prior to any pre-strain and ageing showed certain surface roughness typical of ductile fracture and microscopically a surface covered by dimples of several sizes. However, the solution heat-treated test pieces showed lower decrease in area due to strain ageing. Also solution heat-treated test pieces pre-strained in tension by 5 % and then aged at 100 and 400 ℃ showed transcrystalline character with the dimple morphology. However the dimple size of test pieces decreases with increasing ageing temperature to 400 ℃. This is due to the coalescence of dislocations.

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