

Factors Affecting Kinetics of Strain Aging in S275JRC Steel

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The materials parameter i.e. microstructure as well as the processing factors i.e. aging time and temperature, the amount of plastic deformation, and residual stresses affecting the kinetic of strain ageing in the S275JRC steel were investigated in detail. For this purpose, 5 % pre-strained steel was aged at 160°C for different intervals. The ageing behavior was determined for the as-received (AR) and homogenization & normalizing heat treated (H+N heat treated) conditions. The yield stresses before and after aging process and, the hardness values of the aged steels were considered to calculate strain aging progress. It was shown that a noticeable increase in the yield strength, tensile strength and hardness values was observed for aged AR and H+N heat treated specimens. Moreover, the repetitive increase in the yield and ultimate tensile strength was believed to be a result of strain ageing.

Keywords: S275JRC steel, static strain ageing, mechanical properties

1. Introduction

The time-temperature dependent changes in mechanical properties of plastically deformed metals and alloys are usually defined as strain ageing. It is well described in literature¹⁻⁶, that the materials and processing factors are significant parameters that affect the kinetics of strain ageing in steel. The chemical composition, microstructure, diffusion rate of solute atoms, grain size and crystal system may be considered the most important materials factors, while the aging time and temperature, the amount of plastic deformation, and residual stresses after mechanical operations can be regarded as the processing parameters¹.

General structural mild steels are used various industries due to their attractive strength, ductility and good weldability. The properties of these steel can be controlled by thermo-mechanical methods^{7,8}. These structural mild steels are generally preferred in civil engineering and industry of machinery manufacturing⁹.

Remarkable researches have been carried out on the strain aging of ultra-low carbon, interstitial free; bake hardenable, dual phase and various stainless steel⁹⁻¹⁸. As relatively inconclusive study is available in the literature, a work is needed to investigate the materials and processing factors that are significant parameters affecting the kinetics of strain ageing of S275JRC steel which is preferred for manufacturing heavy vehicle steel wheel rim. This paper focuses mainly on examining the changes in the ultimate tensile and yields strength. The rise in the yield strength due to strain ageing, hardness of AR and H+N heat treated specimens that are aged at a temperature of 160°C for different aging intervals is primary findings in this study.

2. Experimental procedure

2.1. Materials and experimental procedure

The commercially available S275JRC steel used in this study is a plate with a thickness of 6 mm. The chemical composition of S275JRC steel is given in Table 1.

The standard tensile test pieces were prepared according to TS EN ISO 6892-1. The rectangular specimens were machined from the as-received blanks (Figure 1). A group of test samples were kept for AR condition for strain ageing.

In order to obtain homogenized structure, another group of test specimens were heat treated in a furnace for 3 h at $1000 \pm 2^\circ\text{C}$ followed by quenching in the furnace at room temperature. The homogenized test specimens were subjected to normalizing heat treatment for 2 h at $890 \pm 2^\circ\text{C}$ followed by quenching in air at room temperature. The normalizing heat treatment process is considered as solution heat treatment. The schematic of heat treatment process is given in Figure 2.

The AR/H+N heat treated tensile test specimens were pre-strained for 5% in tension. The amount of pre-strain to which each specimen was subjected was measured by marking a gauge length of 32 mm on the specimen and straining was continued until this gauge length extended to 33.6 mm for 5% pre-strain. By considering manufacturing and service condition in which cold deformed heavy duty vehicle wheel rim steel can be heated up to 200°C temperature due to friction lining especially in summer period. To fulfill the conditions, the AR/H+N heat treated and 5% pre-strained specimens were artificially age hardened at 160°C for periods of 10, 20, 30, 45, 60, 90, 120, 150 and 180 minutes in a furnace and subsequently cooled in air. Finally, they were tested using a Schimadzu tensile testing machine at a crosshead speed of 2 mm.min⁻¹. At least three specimens were tensile

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Table 1: The chemical composition of S275RC steel

DIN EN 10025-2:2004	Elements (% weight)								
	C	Mn	P	S	Cu	Si	Ni	V	Cr
S275JRC	0.182	0.949	0.012	0.0002	0.052	0.069	0.025	0.003	0.017

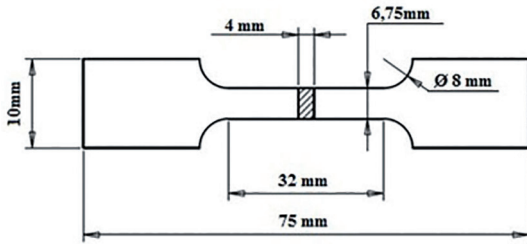


Figure 1: The tensile test sample

tested for each ageing temperature and average values were calculated and used in graphic. The increase in flow stress as a result of restraining was taken as the strain ageing, ΔY_2 , which is illustrated in Figure 3. For samples, pre-strained in tension, ΔY_2 was determined with single specimen by the difference between lower yield stress after ageing and the flow stress at the end of the pre-straining^{16,17}. In this study, ΔY_2 is an increase in the yield strength due to strain aging. It is calculated from an increase or decrease disparity between the strength 5% pre-strained sample and yield strength of aged sample.

The hardness measurement of aged test specimens was carried out using a Universal Hardness Tester (HV_1). In order to eliminate experimental error, five hardness readings were performed per specimens to determine their average hardness.

The microstructure of AR/H+N heat treated and 5 % pre-strained aged test specimens were evaluated through a Nikon Eclipse L150 microscope. The fractured surfaces of

specimens were also analyzed using Carl Zeiss Ultra Plus FESEM trade-mark scanning electron microscope (SEM). The grain size of aged test specimens were measured according to the requirements of the main linear intercepts method. The volume fraction of ferrite phase was also calculated by the point counting method.

3. Results and Discussion

3.1. Strain ageing results

In order to study the effect of the materials parameter such as, the microstructure, and processing factors such as, ageing time and temperature on the ultimate tensile strength (UTS), yield strength (YS), the increase in yield strength due to strain aging (ΔY_2), and hardness of steel were evaluated. The result of the mechanical properties, the volume fraction of phases and the grain sizes of aged steels are given in Table 2. H+N heat treatment process enhanced the yield strength of the S275JRC steel as it should be minimum 275MPa. The mechanical properties are also presented in Figure 4 a) and b).

The values -10°C and 0°C temperature on the X axis refers to the AR/H+N heat treated and 5% pre-strained AR/H+N heat treated samples respectively in Figure 4 a) and b). The variations in UTS, yield strength (YS), strain ageing (ΔY_2) and hardness for varying intervals between 10-180 minutes at 160°C are given in Table 2 and shown in Fig. 4 a) and b) for AR & 5 % pre-strained and H+N heat treated 5 % pre-strained test specimens. It can be observed

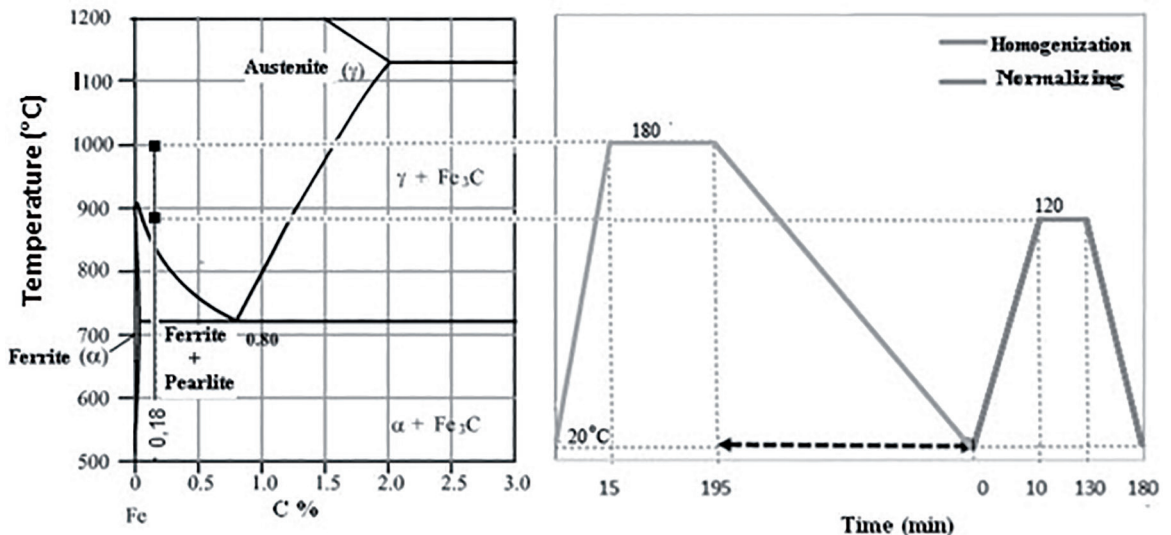
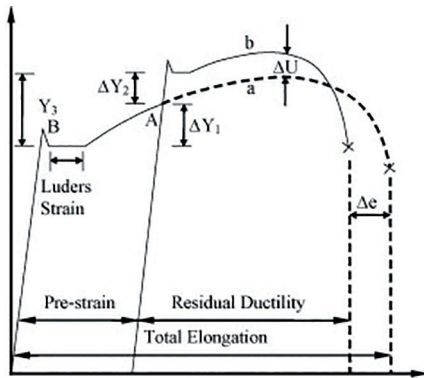


Figure 2: The schematic representation of heat treatment processes



ΔY_1 = Increase in stress produced by pre-strain

ΔY_2 = Increase in stress produced by ageing

ΔY_3 = Increase in stress due to straining and ageing = $\Delta Y_1 + \Delta Y_2$

ΔU = Change in UTS due to straining and ageing

$\Delta \epsilon$ = Change in total elongation due to straining and ageing

Figure 3: Stress–strain curve for low carbon steel strained to point A, unloaded, and then restrained immediately (curve a) and after ageing (curve b).

that as the aging time increases at the temperature of 160°C, a continuous increase in UTS, yield strength (YS), strain ageing (ΔY_2) and hardness is noticed. Peaks in UTS, yield strength (YS), increase in the yield strength due to strain

ageing (ΔY_2) and hardness are observed when the specimen was aged for 20 minutes at the temperature of 160°C in the form of AR and 5 % pre-strained (Figure 4 a). However, UTS, yield strength, (ΔY_2) and hardness were determined for specimen which was aged for 30 minutes at the temperature of 160°C for H+N heat treatment and 5 % pre-strained (Figure 4 b). The strain ageing (ΔY_2) and hardness of test specimens increased approximately by 29MPa and by 12 HV₁, respectively for AR & 5 % pre-strained specimens which were aged at 160°C for 20 minutes while, the strain ageing (ΔY_2) and the hardness increased approximately by 59MPa in strength and by 22HV₁ in hardness, respectively for H+N heat treated & 5 % pre-strained specimens which were aged at 160°C for 30 minutes. An increase in tensile strength, yield strength and (ΔY_2) could be explained by the diffusion of interstitial atoms such as C and N, by creating a Cottrell atmosphere by which mobile dislocations are locked^{4,15,18-21}. The strengthening effect in S275JRC steel could be also explained as a result of interference with the motion of dislocation due to the presence of secondary phase particles such as Fe₃C, nitrides and carbonitrides of alloying elements^{1,14} which could be responsible for increasing the matrix hardness.

In this study, the yield and tensile strength, strain ageing (ΔY_2) and hardness of the AR and H+N heat treated & 5 %

Table 2: The mechanical properties of static strain aged AR&5% pre-strained and H+N heat treated &5% pre-strained samples

Sample	Ageing time	Yield Strength (min)	UTS (MPa)	ΔY_2 (MPa)	Ferrite Phase (%)	Ferrite grain size (µm)	Pearlite grain size (µm)
	As-received	262	404	-	72	8	6.5
AR&5% pre-strain	10	366	416	4	76	9	5,6
AR&5% pre-strain	20	391	439	29	68	7,8	4,5
AR&5% pre-strain	30	341	391	-21	81	9,4	4,1
AR&5% pre-strain	45	330	379	-32	79	8,6	5,6
AR&5% pre-strain	60	360	408	-2	80	10,8	4,9
AR&5% pre-strain	90	371	425	9	82	9,6	4,4
AR&5% pre-strain	120	378	430	16	74	9,7	5,7
AR&5% pre-strain	150	361	408	-1	75	9,1	5
AR&5% pre-strain	180	350	394	-12	79	9,1	5,5
	As-received	262	404	-	72	8	6.5
H+N treated	Hom+Nor.	276	415	-	76	10	4,7
H+N treated &5% pre-strain	10	300	344	-52	74	9,6	6,3
H+N treated &5% pre-strain	20	395	412	43	70	8,3	6,3
H+N treated &5% pre-strain	30	411	430	59	61	8,9	6,4
H+N treated &5% pre-strain	45	375	414	23	77	9,1	6
H+N treated &5% pre-strain	60	349	400	-3	76	8,8	4,9
H+N treated &5% pre-strain	90	387	417	35	71	9,1	6,1
H+N treated &5% pre-strain	120	379	415	27	75	6,2	9,5
H+N treated &5% pre-strain	180	369	390	16	77	10	6

Note: ΔY_2 is an increase in the yield strength due to strain aging. It is calculated from an increase or decrease disparity between the strength 5% pre-strained sample and yield strength of aged sample

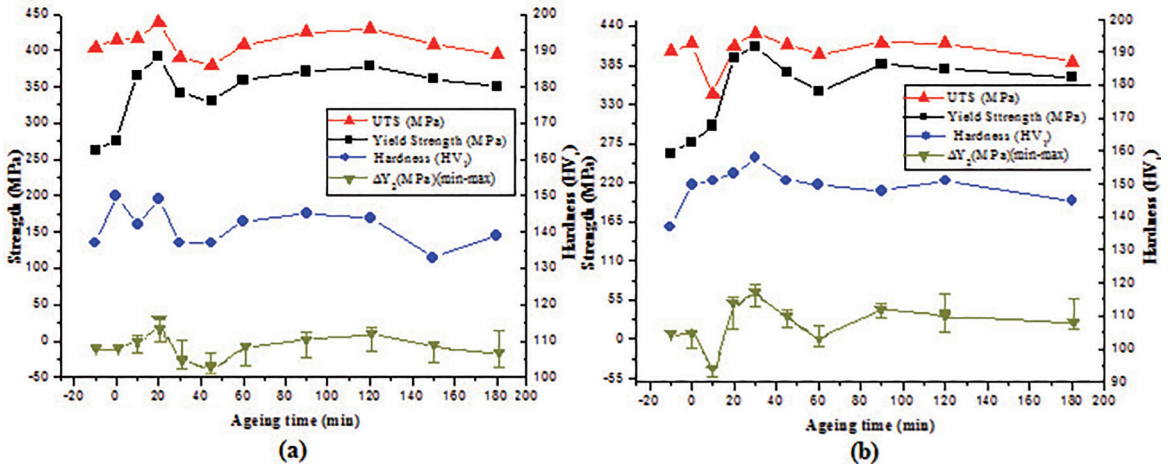


Figure 4: a) UTS, yield strength, (ΔY_2) and hardness versus aging time for AR b) H+N heat treated strain aged test samples

pre-strained test specimens were also studied with ageing time by up to 20 and 30 minutes, respectively. The difference in ageing time, i.e. 10 minutes, introduced a strengthening effect in aged AR test specimens. This effect could be explained by the residual stresses emerging after mechanical working that increases the ageing rate and improves strength reached by conventional ageing by providing homogeneously distributed nucleation sites for precipitation in the matrix¹. Wilson and Russell²² also indicated that in low carbon steel, the increase in strain ageing during the early stages of precipitation is approximately proportional to the number of solute atoms segregating to unit length of dislocation, and is insensitive to the dislocation density. But at higher segregate concentrations continued segregation is less effective in increasing strain ageing, also the strain ageing tends to increase with dislocation density. Since the cold deformation increases an activation energy for diffusion of solute atoms and the distorted crystal structure leads to locking of mobile dislocations, therefore, the strain ageing (ΔY_2) and the hardness increases.

The 5% pre-strain applied prior to ageing to AR and H+N heat treated specimens resulted in marked improvements in (ΔY_2) and hardness. The amount of deformation is also one of the main process parameters affecting the kinetics of strain ageing^{23,24}. Therefore, the higher strength of pre-strained and aged sample (AR and H+N heat treated) can be attributed to the presence of homogeneously distributed precipitates in the matrix²⁵⁻²⁸.

Further increase in the aging time beyond the 20 and 30 minutes at 160°C temperature reduced the UTS, yield strength, (ΔY_2) and hardness of the steel. As seen Table 2, the (ΔY_2) of test specimens decreased approximately by -32MPa for AR and 5% pre-straining conditions, which were aged at 160°C for 45 minutes while, the (ΔY_2) decreased approximately by -3MPa for H+N heat treated and 5% pre-strained specimens, which were aged at 160°C for 60 minutes. The decrease in the (ΔY_2) and hardness could be

due to coalescence of the precipitates into larger particles and dissolution of precipitates which cause fewer obstacles to the movement of dislocation, and also due to annealing out of the defects.

The repetitive increase in the yield strength, tensile strength, (ΔY_2) and hardness of the AR and H+N heat treated and 5% pre-strained test specimen were also determined by ageing time up to 120 and 90 minutes, respectively. The (ΔY_2) and hardness of test specimens for AR & 5% pre-strained then aged at 160°C for 120 minutes increased approximately by 16 MPa and 7 HV₁ respectively, while the (ΔY_2) and hardness of test specimen H+N heat treated & 5% pre-strained then aged at 160°C for 90 minutes increased approximately by 35 MPa, 14 HV₁ respectively. This repetitive increase in (ΔY_2) values of specimens could be attributed to the type of microstructure i.e. the cementite phase in pearlite and the precipitate in dislocation line in S275JRC steel can dissolve during the longer ageing time. The dissolved cementite and precipitates such as carbides of alloying elements can supply solute atoms by backing up the diffusion process for solid solution¹. The solute atoms in the solid solution acts on dislocations therefore, the strength of sample increases repetitively.

Due to over-ageing, a further increase in the ageing time (150-180 minutes) caused marked decrease in tensile strength (UTS), yield strength, strain ageing (ΔY_2) of the steel.

The Figure 5 a) and b) indicates that H+N heat treated test specimens showed slightly higher strength properties than AR test specimens for all ageing intervals. It could be attributed to the homogenization and normalization heat treatment followed by air quenching by which dissolved precipitates and cementite during the solution heat treatment (normalization) supplied higher amount of solute atoms in solid solution. The precipitates and cementite could have not found sufficient time to form again. So, the degree of irregularity in the lattices will cause an increase in the mechanical properties of the H+N heat treated specimens.

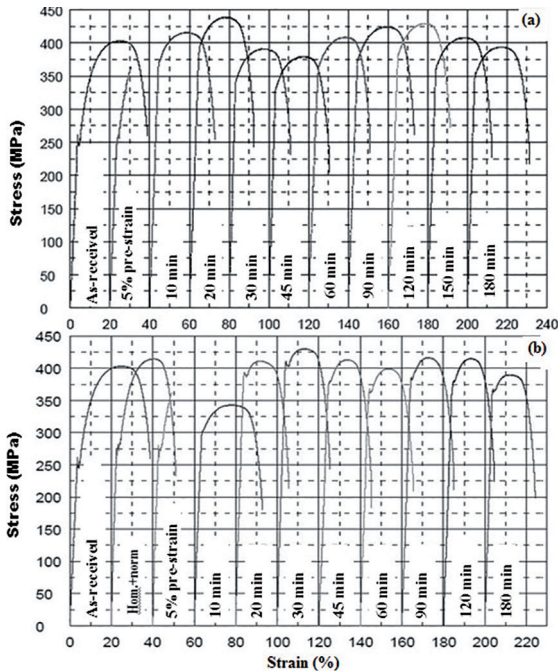


Figure 5: a) Stress-strain curves of AR sample b) H+N sample that aged at 160°C temperature for different interval

The Figure 5 a) indicates that AR test specimens have shown discontinuous yielding behavior due to lamellar pearlitic structure. In other words, the Luder strain is almost suppressed in this steel due to its pearlitic structure as shown in Figure 6. It was reported that in lamellar pearlite, the ferrite layers are too thin to easily allow dislocation multiplication. This causes the Luder strain is reduced or even disappeared as the pearlite volume fraction increases¹. Sylwestrowicz and Hall²⁹ have studied deformation and ageing of the mild steel. They reported that in heavy tensile specimen a complex series of Luder bands may arise, but in thin wire specimens it was shown that only single bands were formed.

However, the Figure 5.b) indicates that H+N heat treated and then aged test specimens showed a continuous yielding

behavior comparable to the AR specimens. Especially, the high nitrogen content has a major impact on reappearance of yield point because of its high atomic mobility and larger solubility at low temperatures as compared to carbon³⁰⁻³². It is believed that too much solute atoms entrapped in the solution during the H+N heat treatment. The Snoek ordering that is short range ordering of interstitial atmosphere, might be also operative during the strain ageing. This phenomenon could explain the return of yield point in a short interval³³.

The Figure 6 and Table 2 also noticeably indicates that the yield strength of the H+N heat treated specimens increased approximately by 14 MPa when compared to the AR test specimens. It is also believed that the homogenized microstructure (see Figure 6 b), rather than finer grain size (see Table 2) is responsible for the increasing the yield strength. It is well known that the microstructure and grain size are considered to be the most important material factors effecting strain ageing.

In general, the strengthening effect of strain ageing in both AR and H+N heat treated specimens was found to be quite low when compared to dual phase carbon steel^{11,14}. This is because of the effect of carbide formers that reduces the interstitial atoms in solid solution. It was reported that the alloying with chromium reduced the rate of strain ageing by ~ 2 times in comparison with non-alloyed low carbon steels³⁴. The carbide and nitride formers like aluminum as a strong nitride former as well as chromium, vanadium, titanium and niobium as carbide/nitride formers can also affect the strain ageing behavior by reducing carbon and nitrogen atoms in solid solution^{17,32,35}.

In addition, the fracture surface of aged test specimen was also investigated in detail. Figure 7 a) - d), shows the fracture surface of AR test piece and aged specimens at 160°C for a period of 20, 45, 120 and 180 minutes while, Figure 8 a) - d) shows the fracture surface of H+N heat treated and 5 % pre-strained test specimen and then aged at 160°C for a period of 30, 60, 90 and 180 minutes.

As seen in Figure 7 and 8, AR and H+N heat treated test specimens showed dimples and cleavage facets, indicating

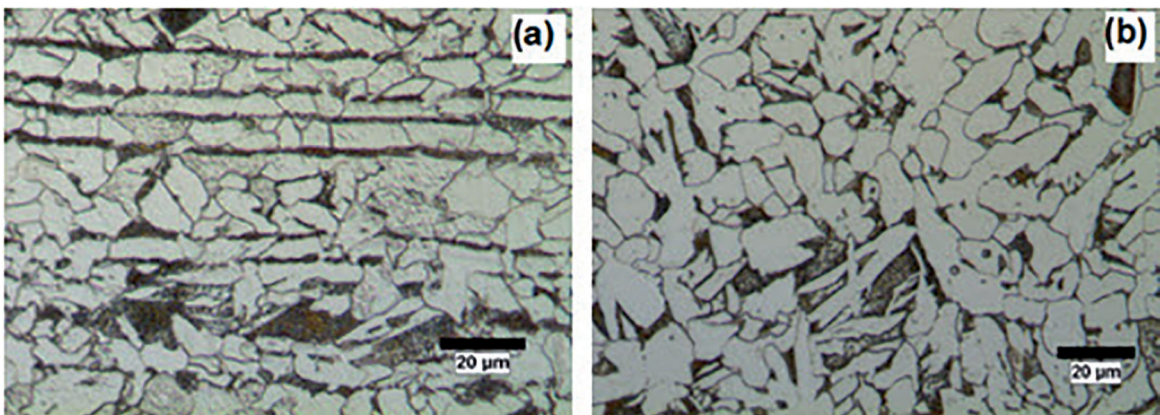


Figure 6: The microstructure of S275JRC steel a) AR, b) H+N condition

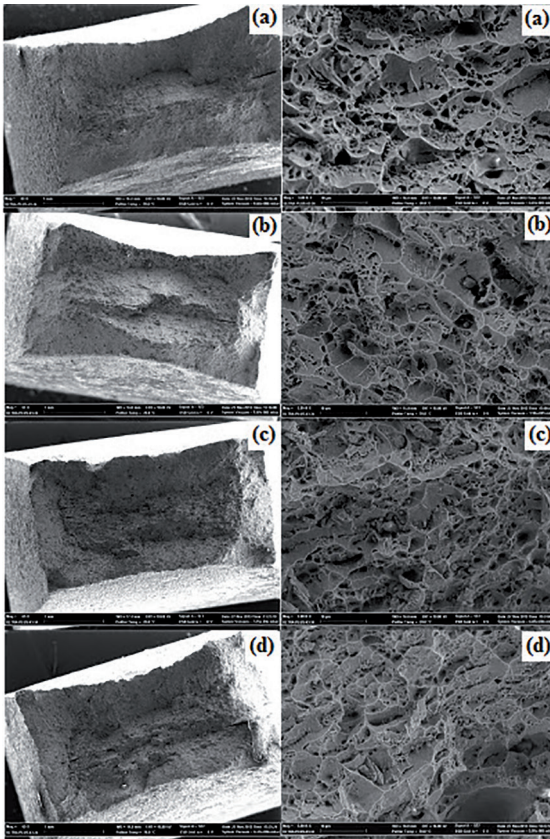


Figure 7: a) The fracture surface of AR test piece aged at 160°C for b) 20, c) 45, d) 120 minutes

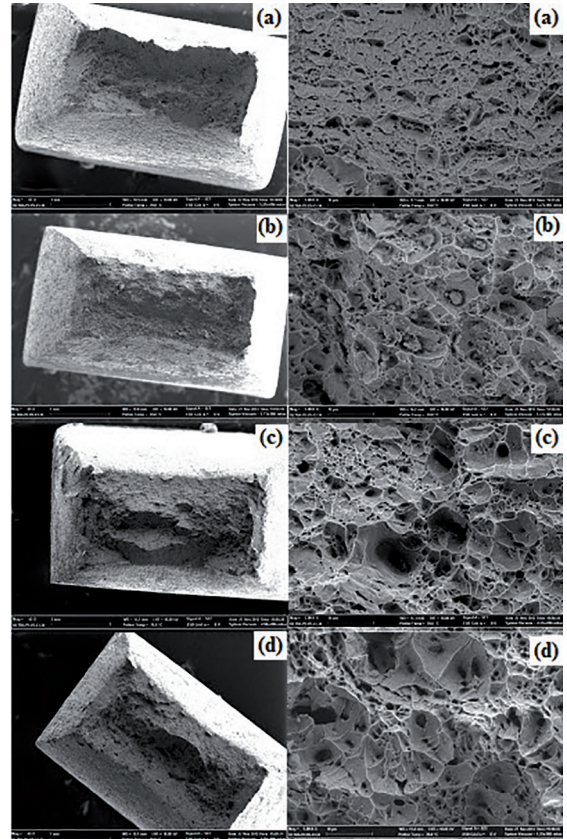


Figure 8: a) The fracture surface of H+N test piece aged at 160°C for b) 30, c) 60, d) 90 minutes

that the fracture is mixed type when the steel was aged at 160°C for a period of 20 and 30 min, respectively. The reduction in cross-sectional area also decreased at 160°C for 20 and 30 minutes ageing time, which corresponds to the embrittlement due to ageing resulting from the interaction between dislocation and precipitate particles. However, AR and H+N heat treated test specimens showed certain surface appearance which is typical of ductile fracture and surface was microscopically covered by dimples of several sizes that were observed after ageing at 160°C for a periods of 45 and 60 minutes, respectively. This leads to an increase in elongation percentage due probably to the coarsening of the precipitates on dislocations. Moreover, the repetitive increase in the tensile strength (UTS), yield strength (YS), strain ageing (ΔY_2) and hardness at the 120 and 90 min ageing time for AR and 5 % pre-strained and also H+N heat treated and 5 % pre-strained specimens, affecting the fracture characteristic of aged steel.

4. Conclusions

The significance of this study results for steel user is that the S275JRC steel used also manufacturing heavy vehicle wheel rim steel can be affected from static load and heats

which are generated by friction lining, weld thermal cycles during the manufacturing process, post weld heat treatment, paint baking or galvanization process. By considering the service condition, an effect of the static strain ageing on the behavior of dynamic load of S275JRC steel should also be investigated.

The conclusions derived from this study can be summarized as follows:

- The material parameters such as microstructure, finer grain size and its distribution, crystal structure and the diffusion rates of solute atoms and processing factors such as ageing time, temperature, quenching rate, pre-straining (amount of plastic deformation) and residual stresses play very important roles in static strain ageing.
- An increase in the tensile strength, yield strength, rising in the yield strength due to strain ageing (ΔY_2) and hardness of AR and H+N heat treated and 5% pre-strained S275JRC steel with an increase in aging time can be explained by a distortion of lattice planes and obstruction of dislocation movement by solute atoms or precipitates.
- The repetitive increase in UTS, yield strength and (ΔY_2) is noticed at the 120 and 90 minutes ageing

times. This repetitive increase in strain ageing (ΔY_2) values of specimens could be attributed to S275JRC steel microstructure in which cementite in pearlite and precipitates in dislocation lines can dissolve during the longer ageing time. The dissolved cementite and precipitates such as, carbides supply solute atoms by backing up diffusion for solid solution. The solute atoms in the solid solution act on dislocations and therefore, the strength of sample is repetitively increased.

- Further increase in ageing time decreases the tensile strength, yield strength, strain ageing (ΔY_2) and hardness of the alloy. This could be due to the coalescence of the precipitates into larger particles which will cause fewer obstacles to prevent the movement of dislocation and hence the mechanical properties begin to diminish.
- Specimens (H+N heat treated and 5% pre-strained) aged at 160°C for some intervals showed higher strength properties than AR aged test pieces for all ageing intervals. It could be attributed to the dissolution of precipitates during the homogenization and following the normalizing heat treatment. So, the more solute atoms in solid solution can cause a degree of irregularity in the lattices.
- In general, the strengthening effect of strain ageing in both AR and H+N heat treated specimens was found to be quite low due to an effect of carbide formers in the S275JRC steel that reduces the interstitial atoms in solid solution.
- Fractographic analysis showed that AR and H+N heat treated test specimens showed dimples and cleavage facets, indicating that the fracture is a mixed type when the alloy was aged at 160°C for a periods of 20 and 30 minutes respectively.

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