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INVESTIGATION OF THE FLOW BEHAVIOUR OF MARTENSITIC STEEL AT ELEVATED TEMPERATURES VIA UNIAXIAL TENSILE TESTS

In recent years, advanced high strength steels have been the main choice of automobile manufacturers due to their excellent strengths and decent formability. In this study, the forming behaviour of a martensitic steel (MART 1200) at elevated temperatures, where higher formability and an acceptable strength can be achieved, has been investigated. For this purpose, tensile test experiments have been conducted at room temperature, 175°C, 275°C, 375°C and 475°C in two different strain rates (0.005 s^{-1}, 0.05 s^{-1}). The flow behaviour, elongation capacity, strain rate sensitivity, strain hardening and strain hardening rate of MART1200 have been investigated and fracture surfaces and microstructures have been examined by scanning electron microscope. It has been shown that the strain rate sensitivity of MART1200 increases significantly after 275°C and, for the higher strain rate, a significant improvement up to 80% in the elongation capacity has been achieved in return for a 19% strength reduction at 375°C.

Keywords: Advanced high strength steel; martensitic steel; warm forming; flow behaviour; tensile test

1. Introduction

Today, increasingly stringent global emission regulations and global safety standards for vehicles place a great deal of pressure on the Original Equipment Manufacturers (OEMs) to produce lighter and stronger parts to keep up with these regulations and standards [1,2]. To meet these safety regulations and fuel emission standards (Euro 1 to Euro 6), advanced high strength steels (AHSS's) have been introduced to the sheet metal forming industry, which has resulted in significant improvements in the strength of the parts while reducing the overall mass due to the reduction of the required thickness of the parts. Martensitic (MART) steels are one of the highest strength steel groups in the AHSS's family making them suitable for use as side impact beams, bumpers, and structural elements where high crash loads are expected [3]. However, the ultra-high strengths of MART steels cause significant problems such as tearing and high spring-back, making them difficult to form into complex shapes, especially at room temperature [4]. Considering the advantages of the warm forming method over cold and hot forming methods such as better stretch flange formability, lower press loads and low oxidation rate, low investment cost, and low energy consumptions, the warm forming method may be an alternative to the hot and cold forming methods to circumvent the problems caused by the low formability of MART steels.

The warm forming method for AHSSs has been shown to procure promising results in various studies [4-6]. For example, Karaağaç et al. [5], have shown that limiting drawing ratio (LDR) of dual phase (DP600) steel could be improved by 22.72% by the warm deep drawing method. In their study, they have increased the temperature of the flange regions of sheet metal to around 300°C and kept the punch contact region around room temperature. The researchers have attributed the increase of LDR to the lowering of flow resistance of the flange regions of sheet metal into the die cavity during deep drawing process. Pepelnjak et al. [7], have applied similar warm deep drawing method for DP600 steel in a numerical simulation and observed a similar increase in LDR around 25.58%. Sen [6], has conducted warm V-bending experiments with MART1200 at four different temperatures (room temperature, 300°C, 400°C and 500°C). The researcher has found that the springback shows a steady decrease up to 400°C, while observing a slight increase at 500°C. The researcher has reported that the decrease in the flow stress of MART1200 with the increase in temperature has resulted in lowering of springback, while the formation of secondary precipitates has caused the increase in springback at 500°C. In a recent study, [8], researchers have analytically shown that warm V-bending is also a successful method for decreasing the springback for MART1400 steels. Sun et al. [4], have conducted uniaxial tensile test experiments with MART1180 steels

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at various temperatures between 25°C to 500°C for different heating and strain rates. They have observed that the ductility of MART1180 steels could be improved by 25.7% by heating the sheets up to 450°C in an ultra-fast heating rate (150°C/s).

In today's sheet metal forming processes at ultra – high strength levels, hot forming is currently one of the most popular method for obtaining parts with strengths above 1500 MPa. However, various problems pertaining to the hot forming method raise doubts about the sustainability of hot forming method. One of the serious problems of hot forming is the high energy requirements due to heating the sheet metals up to austenitizing temperatures over 850°C, in long dwell times in heating tunnels, which require a large space in the workshops [9-13]. In addition, in the hot forming method, after heating the sheet metals to austenitizing temperatures, they need to be moved over the cold dies in order to completely transform the austenite phase to martensite during forming operation. During the transformation of hot metal sheet from the heat tunnel to the cold dies the sheet surface is highly susceptible to oxidation, and this needs to be removed by extra operations such as shot peening, which increases the already high production cost even more [2,14].

In the warm forming method, however, since no quenching is required in the forming process there is no need to introduce a special press tool to the operation and, therefore, a higher productivity can be reached as compared to the hot stamping process. Moreover, since the sheet metal is heated to lower temperatures ($T < 0.5\ T_m$), phase transformation does not occur, and the original microstructure is conserved.

Warm forming has been successfully used for nonferrous metals such as aluminium and magnesium alloy sheets to improve their formability [15,16]. However, there are only a few studies considering the warm formability of AHSS's. In this study, the warm formability of MART1200 has been investigated by analysing its deformation behaviour through warm uniaxial tensile test experiments performed at five different temperatures (room temperature, 175°C, 275°C, 375°C and 475°C) and at two different strain rates (0.005 s^{-1}, 0.05 s^{-1}). Analysis of the deformation behaviour of MART1200 have been carried out by examining the variation of its flow curve, mechanical properties, strain hardening rate, strain hardening exponent, strain rate sensitivity and microstructure under the influence of different temperatures and strain rates.

2. Experimental methods

2.1. Material

In this study, MART1200 steel, supplied from SSAB, in 1.5-mm thickness, was used for the uniaxial tensile test experiments. The chemical composition of the MART1200 was given in TABLE 1. Water jet cutting method was used in order to cut off the tensile test samples to prevent any heat effect on the samples. The tensile test specimens were cut along the rolling direction. The dimensions of the test samples were given in Fig. 1.

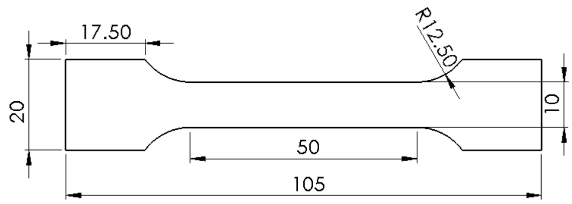

Fig. 1. Dimensions of the tensile test sample for the uniaxial tensile test experiments, (dimensions are in mm)

2.2. Uniaxial tensile tests

Uniaxial tensile tests at room temperature (RT) and elevated temperatures (RT, 175°C, 275°C, 375°C and 475°C) were conducted on a Zwick/Roell Z600 material testing machine. Tensile tests at RT and elevated temperatures were carried out according to ISO 6892-1 and ISO 6892-2 standards, respectively. The tensile tests at elevated temperatures were carried out in a heating chamber where the temperature was controlled to a tolerance of ±15° in three different zones (top, middle, and bottom) After reaching the target temperatures at a heating rate of 10°C/s, samples were held there for 10 minutes in order to homogenously diffuse the temperature in the samples before launching the tensile test. The strain measurements were done according to the movement of the crosshead of the tensile test machine since it was not possible to use an extensometer for the tensile tests at elevated temperatures. Following the tensile tests, the metallographic samples were taken from the homogeneous deformation region of the broken tensile test samples, away from the heterogeneous deformation zone, and tested at a strain rate of 0.05 s^{-1}.

The cross-sections, perpendicular to the test direction were polished and etched with 2% nital for 25 s. FEI Quanta FEG 250 Scanning Electron Microscope (SEM) was used to examine the fracture surfaces and the cross-sections of the broken tensile test samples.

2.3. Analysis of deformation behaviour

The deformation behaviour of the MART1200 at warm forming temperatures was investigated in terms of the variation of its strain hardening exponent, *n*, strain hardening rate, *θ*, and strain rate sensitivity index, *m*, with respect to temperature

TABLE 1

Chemical composition (wt.%) of M1200S and MART1400 steel sheets

Material	C	Si	Mn	P	S	Al	Ti	Nb	V
MART1200	0.097	0.202	1.594	0.010	0.004	0.046	0.037	0.002	0.014

and strain rate. The values of n, θ and m were calculated from the slopes of log true stress-strain and log true stress-strain rate curves in the uniform deformation region where the stresses are in between the yield and ultimate tensile stress. The equations used for the calculation of strain hardening exponent, strain hardening rate and strain rate sensitivity index were given by Eqs. 1-3, respectively.

$$n = \frac{\log \sigma_{true}}{\log \varepsilon_{true}} \tag{1}$$

$$\theta = \frac{d\sigma}{d\varepsilon} \tag{2}$$

$$m = \frac{\log \sigma_{\dot{\varepsilon}_2} / \sigma_{\dot{\varepsilon}_1}}{\log \dot{\varepsilon}_2 / \dot{\varepsilon}_1} \tag{3}$$

where σ_{true} and ε_{true} represent true stress and true strain, respectively, while $\sigma_{\dot{\varepsilon}_2}$ and $\sigma_{\dot{\varepsilon}_1}$ represent true stress values at $\dot{\varepsilon}_2 = 0.005\ \text{s}^{-1}$ and $\dot{\varepsilon}_1 = 0.05\ \text{s}^{-1}$ strain rates, respectively.

3. Results and discussion

3.1. Effect of temperature and strain rate on the flow behaviour of MART1200

Analysing the flow behaviour of a sheet metal is particularly important for forming operations because it describes how the metal sheet behaves during the forming operation. MART steels are one of the highest strength steels among other AHSS's and cause considerable problems such as tearing during forming. To circumvent around such problems warm forming may be an alternative method for forming MART steels due to increased formability provided by warm forming for a reasonable strength loss. In this context, the flow curves of MART1200 obtained in this study at various temperatures and strain rates have been presented in Fig. 2. It is seen that the MART1200 exhibits different nonlinear behaviour during deformation that might be due to the activation of different mechanisms during deformation at different temperatures and strain rates. For example, increasing

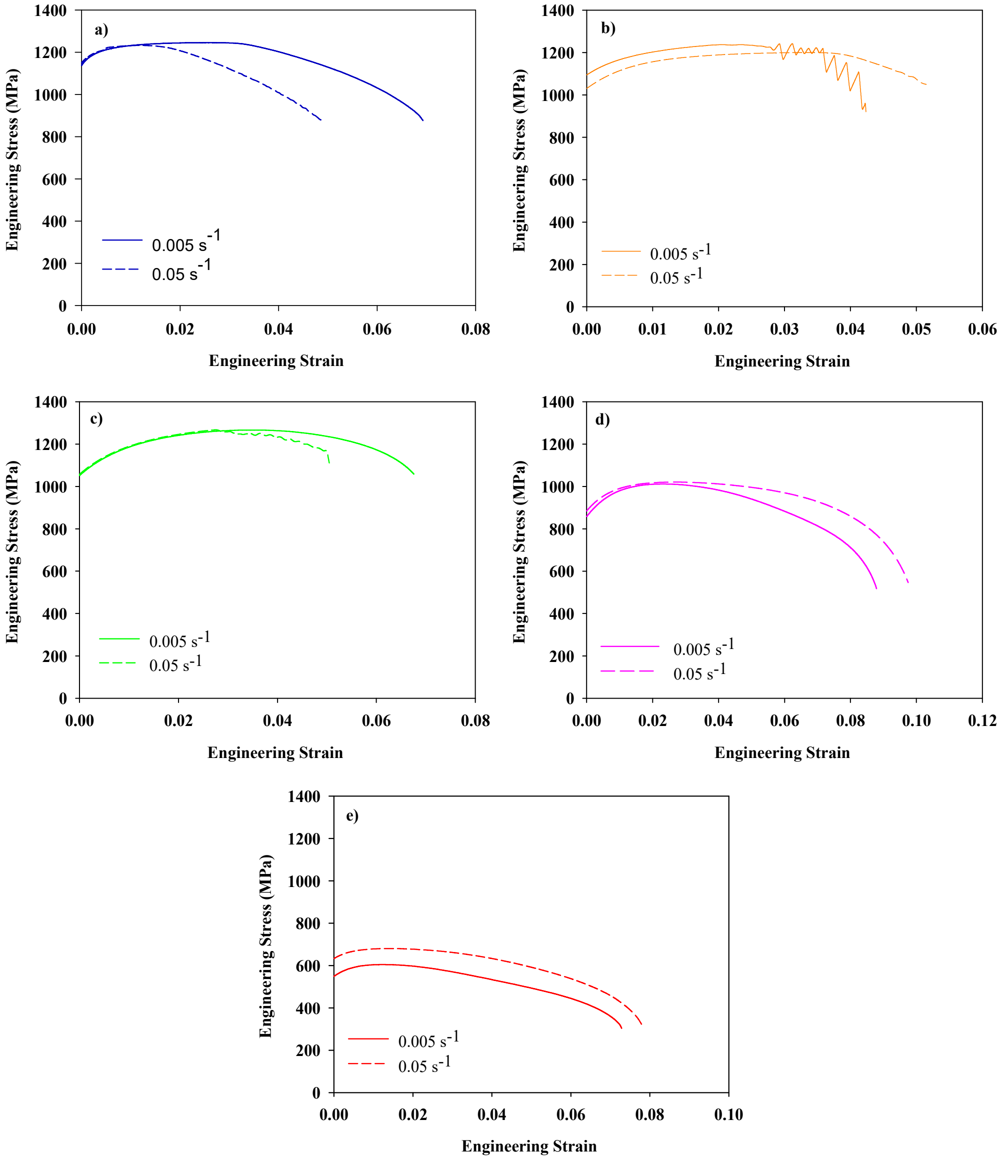

Fig. 2. Effect of temperature and strain rate on the flow curves of MART1200 steels: a) RT, b) 175°C, c) 275°C, d) 375°C, e) 475°C

the temperature from RT to 175°C and 275°C results in dynamic strain aging (DSA) behaviour that significantly restricts material flow and leads to reduction in forming capacity. It is well known that rising temperature in steels causes an increase in the diffusion rate of C atoms in the microstructure [17]. Since the diffusion rate of C atoms closely matches the movement of the dislocations, they constantly block the movement of the dislocations and cause a serrated flow behaviour, resulting in a significant reduction of formability [18], [19]. It can also be noticed that the size of the serrations observed at 175°C is significantly higher than at 275°C. Additionally, it has been observed that the serration behaviour observed at the lower strain rate at 175°C occurred at the higher strain rate at 275°C. This may have been caused because of the fact that the dislocation velocity and diffusion rate vary with temperature and strain rate. DSA occurs when the characteristic time taken for solute atoms to diffuse into temporarily arrested dislocations is of the same magnitude as the dwell time for dislocations to break from localized barriers, which is known to be inversely related to strain rate [20,21]. Therefore, by increasing the strain rate at 175°C, dislocations can break barriers in a much shorter dwell time than it takes for solute atoms to propagate and arrest mobile dislocations. Hence, this may have suppressed serrations at the higher strain rate at 175°C. However, since the diffusion rate of C atoms would be higher at 275°C than it is at 175°C, increasing the strain rate may have an offset timing condition for DSA and may result in the reappearance of serrations at the higher strain rate. By increasing the temperature to 375°C, a significant decrease has been observed in the yield and tensile strength of MART1200 and an improvement in total plastic strain values compared to RT has been noticed. The decrease in strength values of MART1200 may have been due to tempering of the martensitic structure, which may have also increased the overall plastic strain capacity. However, it can be noticed that higher strain rate results in lower overall plastic strain capacity at RT, whereas higher strain rate results in higher overall plastic strain capacity at 375°C. The reason for this difference may be due to the precipitation of cementites in the microstructure, which occurs generally at temperatures above 250°C in MART steels [4,22,23]. It is known that the boundaries between cementite particles and martensite in the microstructure are areas susceptible to cracking and void formation due to the high strength difference between them [4]. Therefore, deformation of the martensitic structure at the lower strain rate may have allowed coarsening of the existing precipitates and increased the area fraction of the precipitates compared to deformation at the high strain rate. This may have reduced the overall plastic strain capacity of the MART1200 for 375°C at the lower strain rate. Further increase in temperature to 475°C has caused further tempering of the martensitic structure and also significant reductions in strength values, which can be attributed to further coarsening of the precipitates. Similar to the overall plastic strain capacity behaviour at 375°C, the higher strain rate deformation of the MART1200 has resulted in higher overall plastic strain capacity for 475°C that may again be attributed to allowing the precipitates to coarsen at the lower strain rate.

3.2. Effect of temperature and strain rate on the mechanical properties of MART1200

3.2.1. Effect of temperature and strain rate on the strength properties of MART1200

Plastic deformation is the result of the movements of line defects in the material lattice, which are called dislocations. Deformation in the material lattice also creates new dislocation defects in the microstructure, and thus, causes the increase of total dislocation density in the microstructure. Accumulating dislocations, entangle each other and block their movements during deformation, and thus, lead to strain hardening of the material [24,25]. The values of yield strength (YS) and tensile strength (UTS) of MART1200 with respect to temperature and strain rate have been given in TABLE 2 and graphically shown in Fig. 3. It can be seen in Fig. 3. that an increase in temperature up to 275°C has not caused a considerable reduction in the UTS values of MART1200 due to DSA, which has been shown to be effective in Section 3.1 at 175°C and 275°C. On the contrary, DSA has caused an increase in the UTS values due to continuous blocking of dislocation lines by diffusing C atoms. YS values, on the other hand, have been observed to be slightly reducing up to 275°C due to tempering effect of martensitic structure. Considerable reductions in the YS and UTS values have been observed after reaching 375°C and the reduction rate has soared by further increase in temperature to 475°C. While the reductions of YS at 375°C as compared to RT for the high and low strain rates have been, respectively, 23.67% and 24.54%, the reductions of UTS have been, respectively, 17.13% and 18.86% for the high and low strain rates. The reductions in YS and UTS values at 475°C have been 45.08% and 44.80% for the high strain rate, 51.71% and 51.44% for the low strain rate, respectively. Tempering of martensitic structure and also the coarsening of existing and newly formed cementite precipitates may have been the main reasons for the considerable reductions in the strength values that have been observed at 375°C and 475°C. It is also known that accumulation of cementite precipitates along the grain boundaries of martensitic structure can cause a reduction effect in the grain boundary strength of martensite particles and prevent them from strain hardening, and thus, due to the decrease in strain hardening ability, considerable strength reductions may have been observed at 375°C and 475°C [4].

3.2.2. Effect of temperature and strain rate on the elongation properties of MART1200

Sheet metal forming processes are generally carried out by stretching the sheet metal over a specific die. Due to this stretching process, various strains such as uniaxial, plane, and biaxial strains are formed on the sheet metal. However, depending on the formability of the sheet metal, the limit strains, where the fracture occurs, can vary significantly. Nakajima tests are conducted to

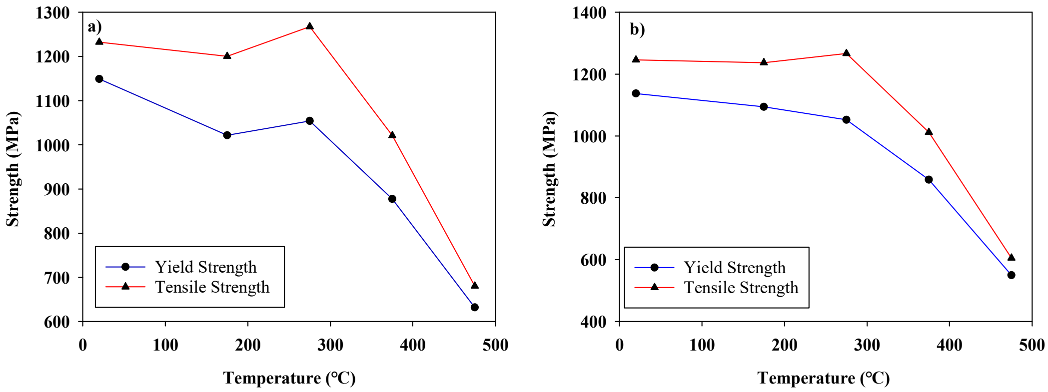

Fig. 3. Variation of yield and tensile strength values of MART1200 with respect to temperature for a) 0.05 s^{-1}, b) 0.005 s^{-1}

determine these limiting strains and show it in a Forming Limit Diagram (FLD). However, uniaxial tensile tests are usually carried out to quickly assess formability of a sheet metal due to its simplicity. Depending on the forming process, strains that are generated can either localise to a certain region or spread uniformly throughout the sheet metal. Therefore, it is important to investigate the elongation capability of a sheet metal in terms of its uniform elongation (UE), post-uniform elongation (PUE) and total elongation (TE) properties. While UE is an indicator of the resisting ability of the sheet metal to global necking phenomenon, PUE is an indicator that shows the ability of the sheet metal to retard the local necking [26]. The variations of UE, PUE, and TE values of MART1200 with respect to temperature and strain rate have been given in Fig. 4.

It can be seen in Fig. 4a and 4b that PUE has considerably reduced at 175°C and 275°C, and been lower than UE. Hence, it is understood that local necking has quickly occurred. It is highly likely that the DSA phenomenon observed at these temperatures has restricted the PUE ability of MART1200. However, it is seen that the PUE ability of MART1200 has significantly improved at 375°C. The further increase in temperature to 475°C, on the other hand, has caused only a subtle change on the PUE ability of MART1200.

The improved PUE ability of MART1200 seen above 275°C may have been caused by the tempering of the martensitic structure. Additionally, the increased cementite precipitates that are formed during heating time may have enhanced the area where fracture progresses by void nucleation, growth and coalescence.

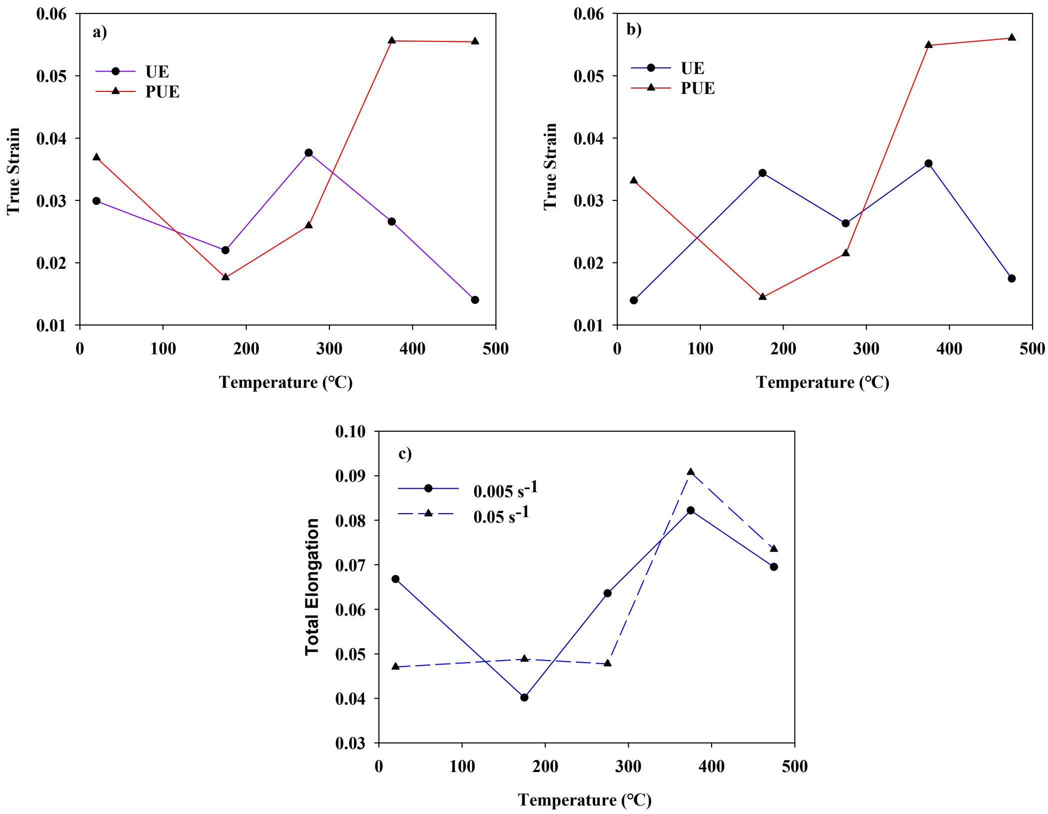

Fig. 4. Uniform Elongation (UE) and Post-Uniform Elongation (PUE) capacities of MART1200 at different temperatures for a) 0.005 s^{-1}, b) 0.05 s^{-1} and c) total elongation (TE) capacity of MART1200 for each strain rate

TABLE 2

Yield and tensile strength values of M1200S at different temperatures and strain rates

Material			
MART 1200			
Strain Rate (s^{-1})	Temperature (°C)	YS (MPa)	UTS (MPa)
0.05	20	1149	1232
0.005	20	1137	1246
0.05	175	1021	1200
0.005	175	1094	1237
0.05	275	1054	1267
0.005	275	1052	1266
0.05	375	877	1021
0.005	375	858	1011
0.05	475	631	680
0.005	475	549	605

The reason for the almost unchanging PUE ability of MART1200 at 475°C as compared to 375°C, may have been caused by further tempering of MART1200 and at the same time, formation of excessively coarsened and accumulated cementite precipitates at the grain boundaries. It is known that cementite precipitation at the grain boundaries can significantly reduce the grain boundary strength of martensitic structure [4].

While the tempering of martensitic structure has improved the PUE, the excessively coarsened precipitates might have increased the damage progression rate and reduced the PUE ability of MART1200. Therefore, a similar PUE ability might have been observed due to the two counter-fitting effects observed at 475°C.

In Fig. 4a, it is seen that UE capacity of MART1200 has sharply reduced at 175°C, reached a peak value at 275°C and then started reducing linearly at the higher temperatures. Serrated flow behaviour observed at 175°C seems to have restricted the uniform flow of the material and reduced the UE ability of MART1200. Fine cementite precipitates formed inside the martensite structure are known to be sources of additional strain hardening since they hinder the movement of dislocations [27]. Thus, fine cementite precipitates that might have been formed at 275°C in the martensitic structure might have increased the strain hardening and, therefore, caused an increase in the UE ability of MART1200 for the lower strain rate. The further increase in temperature has led to an enhanced tempering of martensitic structure, and caused the coarsening of precipitates. Therefore, UE ability of MART1200 has continuously decreased for the lower strain rate with the increase of temperature to 375°C and 475°C. As shown in Fig. 4b, UE ability of MART1200 at the higher strain rate has initially increased at 175°C, after a decrease at 275°C, has recovered back at 375°C and then sharply reduced at 475°C. The initial increase in UE ability at 175°C has probably been caused by the formation of fine precipitates in the martensite grains as explained earlier. Later decrease in the UE ability has been caused by the serrated flow at 275°C. Unlike the linear decrease in UE ability observed at 375°C for the lower strain rate, UE values have recovered back and been even higher than RT for higher strain rate. It is well known that the increase in strain rate improves the strain hardening and, thus, the UE ability, of materials that exhibits positive strain rate sensitivity. Hence, due to the increase in strain hardening at the higher strain rate, UE ability of MART1200 at 375°C has considerably improved by 35% as compared to the lower strain rate. The tempering of martensitic structure and excessive coarsening of precipitates in the microstructure at 475°C, has diminished strain hardening ability of MART1200 and resulted in the loss of UE ability. However, due to the enhanced strain hardening with the increase of strain rate, UE ability at 475°C has been around 24% higher as compared to the lower strain rate. As shown in Fig. 5c, the highest TE has been observed to be obtained at 375°C at the higher strain rate. Obtained TE values for the higher strain rate have been 0.05, 0.05, 0.05, 0.09 and 0.07 at RT, 175°C, 275°C, 375°C and 475 °C, respectively. Obtained TE values for the lower strain rate have been 0.06, 0.04, 0.06, 0.08, 0.07 at RT, 175°C, 275°C, 375°C and 475°C, respectively. Hence, the TE of MART1200 at 375 °C for the higher strain rate has increased about 80% as compared to RT. However, the increase of TE at 375°C for the lower strain rate as compared to RT has been around 25%. Therefore, it is understood that considerable improvement in the formability of MART1200 steel can be achieved at 375°C and 475°C. However, the improvement of TE is strongly enhanced at the higher strain rate. In a study conducted by Sun et al. [4], similar results have been found where they have shown the increased TE at higher strain rates at warm-forming temperatures. Considering the TE improvement (80%) and the reduction of UTS (17.13%), achieved at 375°C, the optimum warm temperature can be selected as 375°C in between the investigated temperatures.

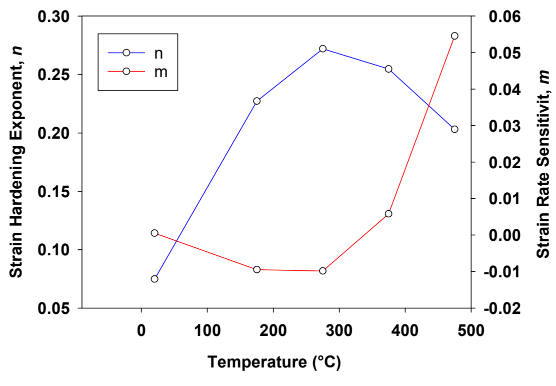

Fig. 5. Variation in the strain hardening exponent and strain rate sensitivity with respect to temperature

3.4. Effect of temperature and strain rate on strain hardening and strain rate sensitivity indices

The exponents of strain hardening, and strain rate sensitivity are the two important parameters, which significantly affect the behaviour of a sheet metal during a forming operation. The strain hardening improves the resistance of sheet metal to necking by strengthening the material. Thus, higher strain hardening exponents are generally desired for the sheet metals that undergo plastic deformation [28]. The strain rate sensitivity behaviour of sheet metal, on the other hand, considerably affects the limits of the material to accommodate localised deformations [29]. In addition, a high strain rate sensitivity enhances the crash worthiness performance of the sheet metal during an accident, since it causes strengthening of the material by strain rate [30]. In contrast to the advantageous effects of positive strain rate sensitivity, if the material exhibits negative strain rate sensitivity, it causes in significant disadvantages for the formability of sheet metal since negative strain rate sensitivity indicates the DSA behaviour [19]. The effects of temperature on the strain hardening exponent and strain rate sensitivity behaviour on the MART1200 have been shown in Fig. 5. It can be seen that strain rate sensitivity has reduced to negative values at 175°C and 275°C and then started increasing steeply with the further increase in temperature to 375°C and 475°C. DSA behaviour observed at 175°C and 275°C has probably been the main reason for the negative strain rate sensitivity observed at these temperatures. Upon forming a global neck in the specimens during tensile testing, deformation localises to that region, the strain rate locally increases and the sheet metal starts hardening by strain rate in the neck region. Thus, a high strain rate sensitivity plays a major role in improving the PUE ability or local deformability of the sheet metal [31]. Therefore, the increase in the strain rate sensitivity at 375°C and 475°C has been one of the main reasons for the enhanced PUE ability of MART1200 at these temperatures. Generally high strain rate sensitivity values around 0.2 or higher are obtained at hot working conditions [32]. In the warm forming temperature range, strain rate sensitivity values are considerably lower than what can be achieved in hot working conditions. Hence, the obtained strain rate sensitivity values in this study have been 0.005 at 375°C and 0.054 at 475°C. It is also worth noting that the increase of temperature up to 475°C has significantly raised the strain hardening exponents as compared to RT. As the moving dislocations are pinned by solute atmosphere in the DSA temperature region, dislocation multiplication before the re-pinning increases the increment of dislocation density per strain, which contributes to the increase in work-hardening rate. In addition, the resultant planar-slip dislocation structures with cumulative strain can act as the effective obstacles to dislocation movement, which further lead to a higher work-hardening ability [33]. The increase of temperature from 275°C to 375°C and 475°C has led to a linear reduction in the strain hardening exponent due to the further tempering of martensite structure. Strain hardening is one of the most important factors of sheet metal forming since it inhibits the necking phenomenon. Thus, a high and sustaining strain hardening during deformation considerably contributes to the formability of sheet metal. Thus, it is important to carefully examine the strain hardening rate behaviour of sheet metal during its deformation. In Fig. 6, the strain hardening rates of MART1200 at different temperatures and strain rates have been shown. As shown in Fig. 7, the initial strain hardening rate of MART1200 at RT has been significantly high as compared to the initial strain hardening rates at the elevated temperatures. However, it can be seen that the strain hardening rate at RT has rapidly reduced and, after around 0.001 strain, it has been lower than the strain hardening rates that are observed at all the elevated temperatures except at 475°C. The initial strain hardening rate at 475°C has been significantly lower than any other temperatures and, strain hardening rate has reached zero at a lower strain level than RT. At higher temperatures, the more favourable dislocation cross-slip significantly contributed to the enhancement of dislocation mobility. The occurrence of dynamic recovery accelerated the dislocation annihilation, which is responsible for the decreased work-hardening ability [34]. Tempering of the martensitic structure at elevated temperatures has led the MART1200 to strain harden at a higher rate. However, further tempering effect and the coarsening of cementite precipitates have caused a considerable decrease in the strain hardening rate at 475°C.

3.5. Effect of temperature on the fracture morphology and microstructure of MART steels

In the warm forming method, the working temperatures are kept within a specific range so that significant changes in the microstructure are avoided and the strength of the material is mostly preserved. Therefore, the examination of the microstructure and as well as the fracture surfaces play an important role in understanding the changes in the behaviour of the material. The fracture surface images of MART1200 broken at different

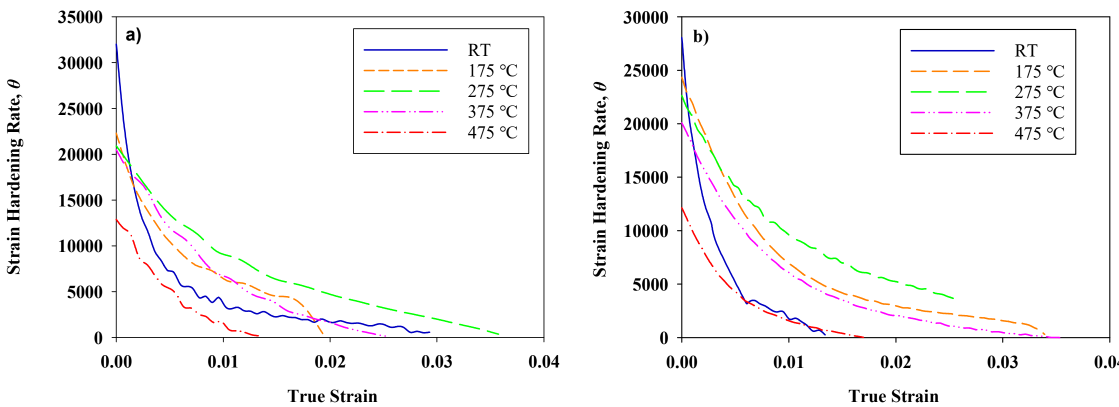

Fig. 6. Effect of temperature on the strain hardening rate behaviour of MART1200 for a) 0.005 s^{-1} and b) 0.05 s^{-1} strain rates

temperatures for 0.05 s^{-1} strain rate have been shown in Fig. 7. It is seen that MART1200 has fractured in a ductile manner at RT, 175°C, 375°C and 475°C, as understood from the considerable amount of dimples that exist in the fractured surfaces. However, it can be noted that a large portion of the area of the fracture surface of the sample fractured at 275°C has consisted of a flat or smooth region. Thus, it is understood that the fracture has occurred in a highly brittle manner at 275°C. As shown earlier in Fig. 2, significant serrations have occurred at 275°C due to the influence of DSA. Ekrami [35], has also reported the DSA behaviour in this temperature range. It is known that the occurrence of DSA is also the responsible factor for the formation of flat and featureless fracture surface with small-sized dimples [36]. Similarly, flat regions have been observed to coexist with the dimpled structure on the surface of the sample fractured at 175°C, which has caused the fracture surface to look smoother than it is at RT. It is noteworthy that fracture surface areas have significantly reduced with the further increase in temperature after 275°C, however, a slightly larger area reduction has been observed at 375°C as compared to 475°C. The reason for the significant area reductions that have been observed at 375°C and 475°C can be explained by the considerable improvement in the strain rate sensitivity (Fig. 5) and the PUE ability (Fig. 4) of MART1200. The slightly larger fracture area that has been observed at 475°C as compared to 375°C can be attributed to the considerable reduction of strain hardening and as well as the UE capability of MART1200, which has probably been caused by the coarsening of precipitates in the microstructure. Partial tempering of the martensite also contributes to the softening mechanisms during high temperature deformation processing of DP steels [35].

The decreasing trends observed in YS, UTS, and as well as in the work hardening parameters, *K* and *n,* at temperatures

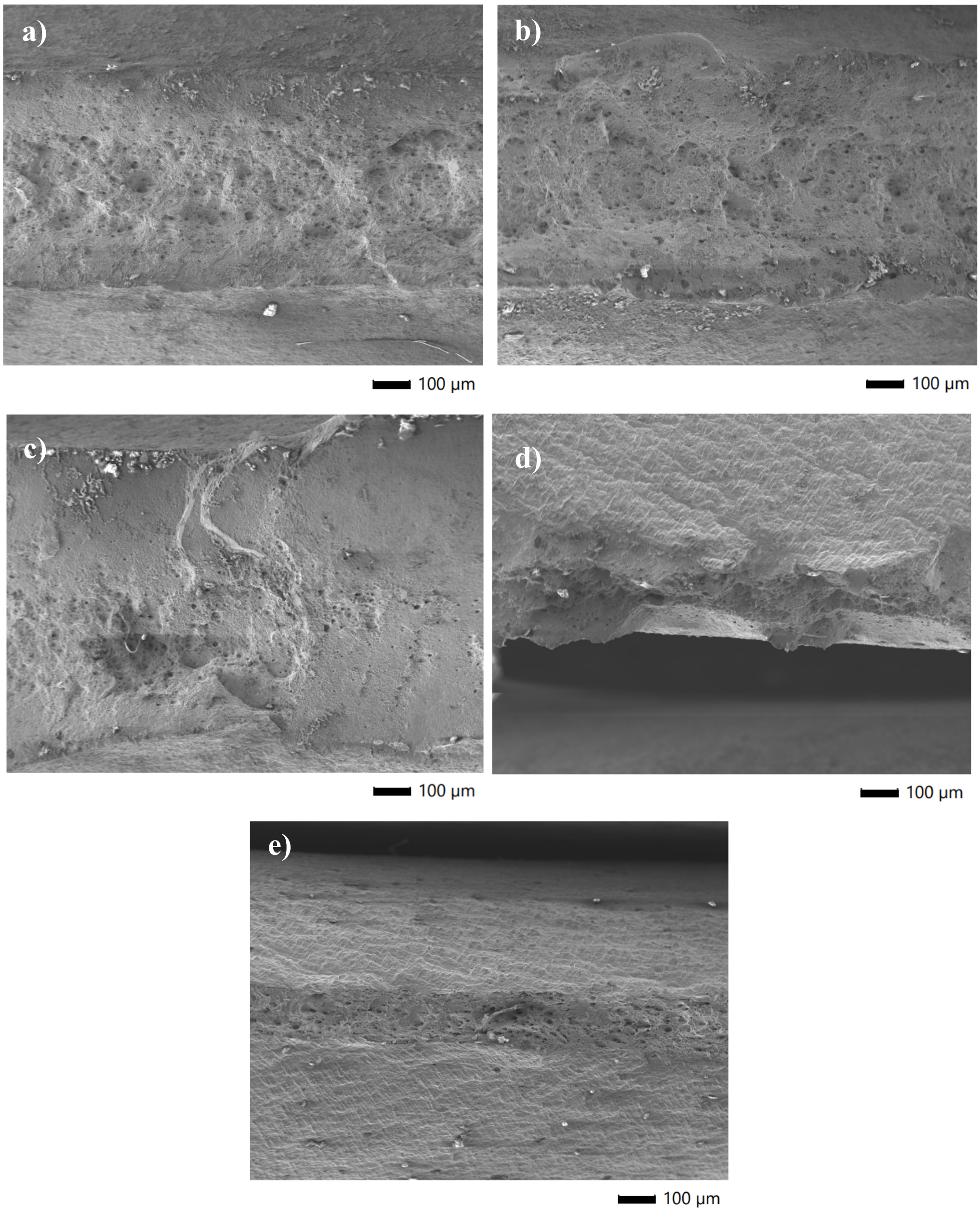

Fig. 7. Fracture surfaces of MART1200 deformed at a) RT, b) 175°C, c) 275°C, d) 375°C and e) 475°C at 0.05 s^{-1}

above the DSA region could be attributed to this mechanism [37]. While most dimples that have been observed on the fracture surfaces of the samples fractured at RT, 175°C, 375°C have been homogenous in size, considerably large and small dimples have been found to have formed at 475°C. The larger dimples found at 475°C might have occurred due to the growth of cementite precipitates formed in the martensitic structure. Larger cementite precipitates might have initiated earlier void nucleation and caused an earlier fracture of the sample as compared to 375°C, which explains the slightly larger area reduction observed at 375°C as compared to 475°C and as well as the lower uniform elongation capability at 475°C. The microstructures of MART1200 deformed at different temperatures for 0.05 s^{-1} strain rate have been shown in Fig. 8. As shown, MART1200 has consisted of a fully lath-type tempered martensitic structure. Small amounts of precipitates have been observed to have already existed in the microstructure at RT. It has been noted that the size and the number of precipitates have been similar at RT, 175°C and 275°C, however, a significant rise in the number of precipitates has been observed by the further increase in temperatures to 375°C and 475°C.

The cementite particles observed in the martensitic structure at RT might have been formed due to the production method of as-received MART steels

The increase of temperature, however, especially after reaching 250°C, causes the cementite precipitates to coarsen and form spheroids in the microstructure [38].

However, submicron sized precipitates might have been formed in the microstructure at 175°C, which explains the higher strain hardening exponent observed at the elevated temperatures as compared to RT. Since the precipitates are the obstructions for the dislocations to freely move in the lattice structure, they

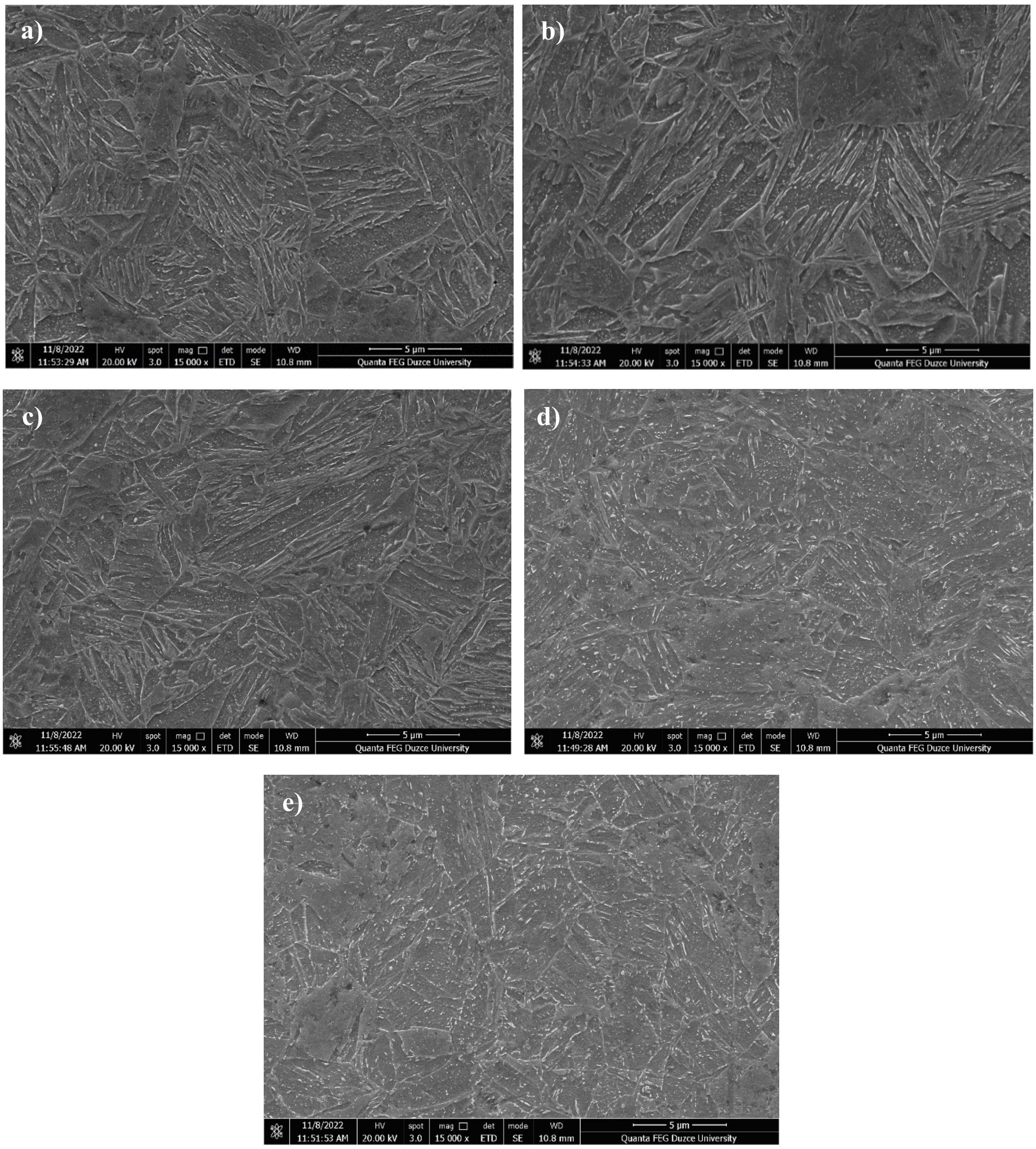

Fig. 8. The SEM images of MART1200 deformed at a) RT, b) 175°C, c) 275°C, d) 375°C and e) 475°C temperatures at 0.05 s^{-1} strain rate

significantly contribute to strain hardening [27]. The excessively coarsened precipitates may have increased the void coalescence mechanism and caused an earlier fracture of the sample at 475°C as compared to 375°C.

4. Conclusions

In this study, the deformation behaviour of MART1200 at elevated temperatures was investigated. The principal conclusions that have been drawn from the study have been listed below.

- The deformation of MART1200 steel at 175°C and 275°C has caused severe serrated flow due to the DSA effect. DSA effect has considerably limited the TE ability of MART1200.
- While obtained TE values at RT, 175°C, 275°C, 375°C and 475°C have been, respectively, 0.05, 0.05, 0.05, 0.09 and 0.07 for the higher strain rate, they have been, respectively, 0.06, 0.04, 0.06, 0.08, 0.07 for the lower strain rate. Hence, the highest TE has been achieved at 375°C for both strain rates.
- It has been found that deformation of MART1200 in the higher strain rate at the elevated temperatures above 275°C is more advantageous in terms of TE improvement as compared to deformation in the lower strain rate. TE at 375°C has improved by around 80% for the higher strain rate, while the improvement has been around 25% for the lower strain rate.
- TE ability of MART1200 has been observed to have slightly decreased at 475°C as compared to 375°C. The significant increase in the number of cementite precipitates that have been observed in the microstructures at 475°C has been thought to be the reason leading to a slight reduction in TE.
- Reductions in the YS and UTS values have been only noticeable above 275°C. The reductions in YS for the high and low strain rates at 375°C have been, respectively, around 23.67% and 24.54%, while the UTS has decreased by 17.13% and 18.86%, respectively.
- The YS and UTS values have significantly decreased at 475°C. The observed reductions in YS and UTS values at 475°C have been 45.08% and 44.80% for the high strain rate, 51.71% and 51.44% for the low strain rate, respectively.
- A considerable rise in the strain hardening exponent has been observed up to 275°C. However, the further increase in temperature has led to a reduction of strain hardening exponent. Tempering of martensitic structure as well as formation and increase in cementite precipitates have been thought to be the reason for the reduction of strain hardening exponent at temperatures above 275°C. However, strain hardening exponents obtained at all the elevated temperatures have still been considerably higher than the strain hardening exponent observed at RT. It has been suggested that the probable formation of submicron-sized cementite precipitates at the elevated temperatures could have been the cause for the increased strain hardening exponents.
- Negative strain rate sensitivity values have been observed at 175°C and 275°C, however, further increase in temperature to 375°C and 475°C has led to a considerable increase in the strain rate sensitivity. The increase in strain rate sensitivity at temperatures above 275°C has been thought to be the major impact for the improved PUE ability of MART1200.
- The microstructure images of MART1200 have shown that considerable precipitate formation has occurred at 375°C and the precipitates have further coarsened along the grain boundaries at 475°C.

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