Effect of Si, Al and Mo Alloying on Tensile Properties Obtained by Quenching and Partitioning

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Keywords: Quenching & Partitioning, AHSS, Martensite, Retained Austenite

Abstract

Quenching and Partitioning (Q&P) is receiving increased attention as a novel heat treatment to produce advanced high strength steels (AHSS). Alloying effects on retained austenite stabilization have been reported previously with molybdenum increasing the austenite fractions and reducing the sensitivity to partitioning time whereas partial replacement of silicon by aluminum results in lower fractions especially for longer partitioning times. The present work reports mechanical properties obtained by Q&P in these alloys. Unprecedented tensile strength and ductility combinations are obtained, when compared to the properties of lean AHSS steels processed by conventional routes. Strain hardening shows a pronounced dependence on partitioning conditions. Instantaneous strain hardening versus true strain plots with an upward slope are obtained at longer partitioning times and higher partitioning temperatures suggesting an effective contribution of the TRIP mechanism. It is therefore important to obtain significant austenite fractions following partitioning at higher temperatures and/or longer times.

Introduction

A significant research effort has been devoted to the development and application of advanced high strength steel grades (AHSS). This research was mainly driven by automotive industry aiming at reducing weight in order to increase gas mileage, improving passive safety and competing with light-weight materials such as Al and Mg alloys. The primary goal in the development of the grades has always been an increase in strength without significant loss in ductility. A variety of steel grades have since been developed such as Dual Phase (DP), Transformation Induced Plasticity (TRIP), Twinning Induced Plasticity (TWIP), Complex Phase

(CP), etc. The AHSS can be divided into two groups as shown in Figure 1 [1,2]. The so-called first generation AHSS have multiphase microstructures consisting of mixtures of ferrite and martensite (DP), ferrite and bainite containing retained austenite (TRIP), etc. Lean alloying is used resulting in cost-effective grades. The second generation AHSS consists of highly alloyed austenitic steels; these steels clearly exhibit superior properties, albeit at a much more significant cost. It is apparent from Figure 1 that an important gap exists in the tensile strength versus total elongation diagram between the properties exhibited by the first and second generation grades. Novel developments in AHSS research may hence focus on obtaining these properties at a desired lower alloying cost than needed for the second generation grades.

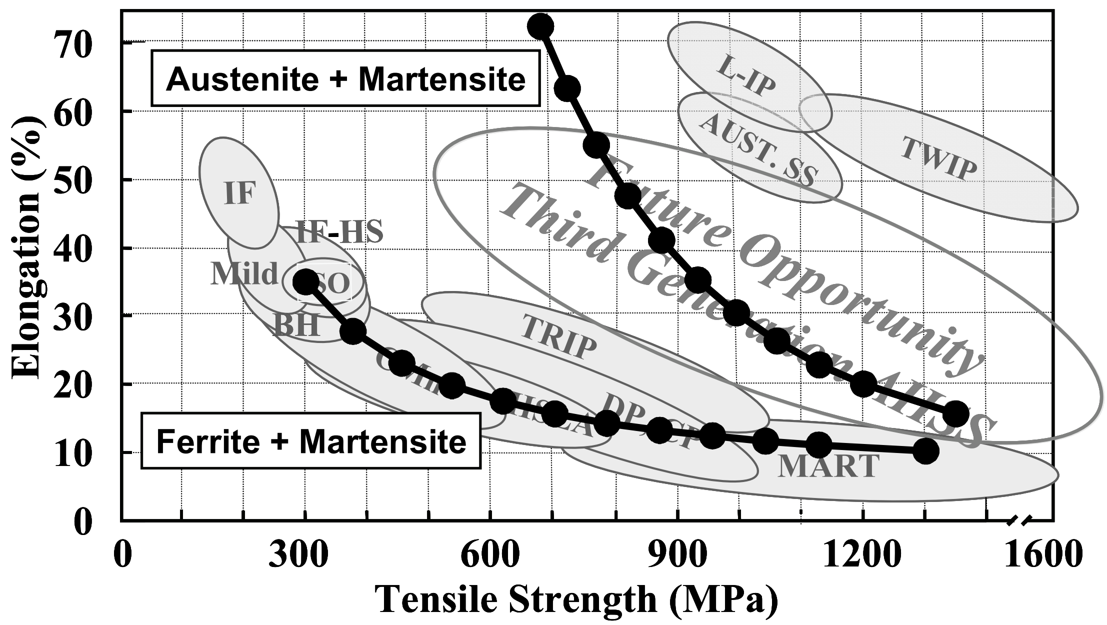


Figure 1 Situation of developed AHSS grades on an elongation versus tensile strength diagram. Predicted elongation/tensile strength combinations of hypothetic ferrite/martensite and austenite/martensite microstructures are also given [1,2]. A property region for future AHSS development is identified.

Matlock *et al*. proposed a model to predict the mechanical properties of hypothetic microstructures consisting of mixtures of ferrite and martensite or martensite and austenite [1,2]. The resulting property combinations are also given in Figure 1. The properties predicted for the ferrite/martensite microstructures overlap with the property band obtained by the first generation of AHSS. The predicted properties for martensite/austenite mixtures are situated in the region unfilled by the developed AHSS of second and third generation.

A new process, called Quenching and Partitioning (Q&P) has recently been proposed as a way of producing martensite along with significant fractions of retained austenite [3]. The heat treatment consists of two steps. After soaking in the intercritical region or above the A_3 temperature, the steel is quenched, to a pre-determined temperature QT in the M_s-M_f region. A partially martensitic, partially austenitic microstructure is present at this stage. In a second, so-called partitioning step, the steel is either maintained at the QT or brought to a higher temperature PT. The aim of the latter step is to carbon stabilize the austenite present at the QT by carbon depletion of the martensite and transport to the austenite. After final quenching to room temperature, a martensitic microstructure containing significant volume fractions of carbon stabilized retained austenite is obtained. Vital for the Q&P process is the retardation of carbide formation. Alloying with Si, Al and/or P is hence required, making lean TRIP compositions suited for Q&P processing. Significant retained austenite stabilization has been reported by the Q&P process [4,5,6,7,8]. The present contribution reports tensile properties obtained by Q&P processing of steel grades alloyed with Si, Al and Mo.

Experimental Procedure

The chemical compositions used in present study are given in Table 1. Note that an underscore is used to denote a higher carbon content. The material was received in the cold-rolled state with a thickness of 1 mm. Tensile specimens were machined in the rolling direction according to the A50 geometry [9]. Heat treating was done using salt pots and involved full austenitization, quenching to the appropriate quench temperature, holding for 3 s, followed by a partitioning treatment before final water quenching to room temperature. The method proposed by Speer *et al*. [3] was used to estimate the quench temperatures predicting the highest austenite fractions. Three partitioning temperatures, 350, 400 and 450 °C were used for 10, 60, 120, 180, 240 and 300 s. Retained austenite fractions were measured by magnetic saturation [9]. Tensile properties were determined by uni-axial tensile testing on a screw-driven tensile frame. A 50 mm gauge extensometer was used.

Table 1 Chemical composition (in wt%) and calculated optimum quench temperature QT (in °C) [8].

	C	Mn	Si	Al	Mo	QT
CMnSi	0.20	1.63	1.63	-	-	240
$\underline{C}$MnSi	0.24	1.61	1.45	0.30	-	250
$\underline{C}$MnAlSi	0.25	1.70	0.55	0.69	-	260
Mo$\underline{C}$MnAl	0.24	1.60	0.12	1.41	0.17	270
MoCMnSi	0.21	1.96	1.49	-	0.25	240

Retained Austenite Stabilized by Quenching and Partitioning

The retained austenite fractions stabilized by Q&P following full austenitization in the grades given in Table 1 have been reported previously [8] and are given in Figure 2. Continuously decreasing austenite fractions are observed with increased partitioning time for the CMnSi grades as shown in Figure 2a. In general, similar fractions are obtained for both grades. Partitioning temperature does not show a pronounced effect on the obtained fractions. At short times (Pt < 120 s) slightly higher fractions are obtained at the lowest partitioning temperature whereas at longer times (Pt > 120 s) slightly lower fractions are obtained at the highest partitioning temperature. The effect of partial replacement of Si by Al is illustrated in Figure 2b. Significantly lower fractions are obtained for the $\underline{C}$MnAlSi grade at similar partitioning conditions. The highest fractions are obtained following partitioning at 350 °C and the fractions decrease continuously with increased partitioning time for all tested partitioning temperatures. The effect of Mo additions to a CMnSi grade is reflected in Figure 2c. Higher fractions are obtained and a reduced sensitivity to increased holding at the partitioning temperature is observed. Increasing the partitioning temperature results in an increase of the retained austenite fractions. In order to evaluate whether the beneficial effect of Mo on austenite stabilization can compensate the detrimental effect of Al, a Mo$\underline{C}$MnAl alloy was also tested and the results are shown in Figure 2d. Lower fractions are obtained for the Mo$\underline{C}$MnAl grade compared to the $\underline{C}$MnAlSi grade. The highest fractions are obtained for a partitioning temperature of 350 °C where similar fractions are obtained compared to the CMnAlSi grade. The fractions decrease with increased partitioning time. Hence, the effect of the replacement of Si by Al is not compensated by the Mo additions employed here.

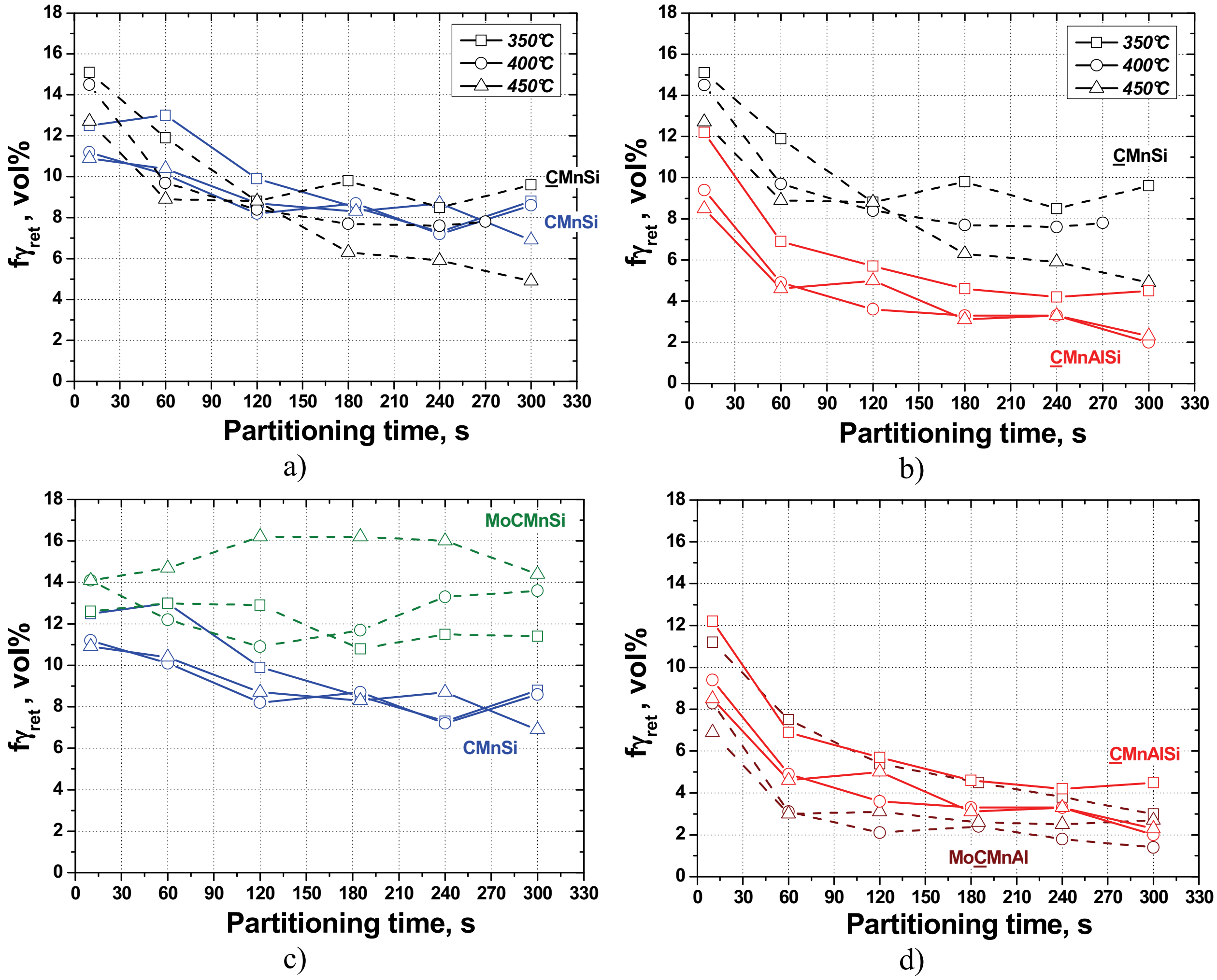
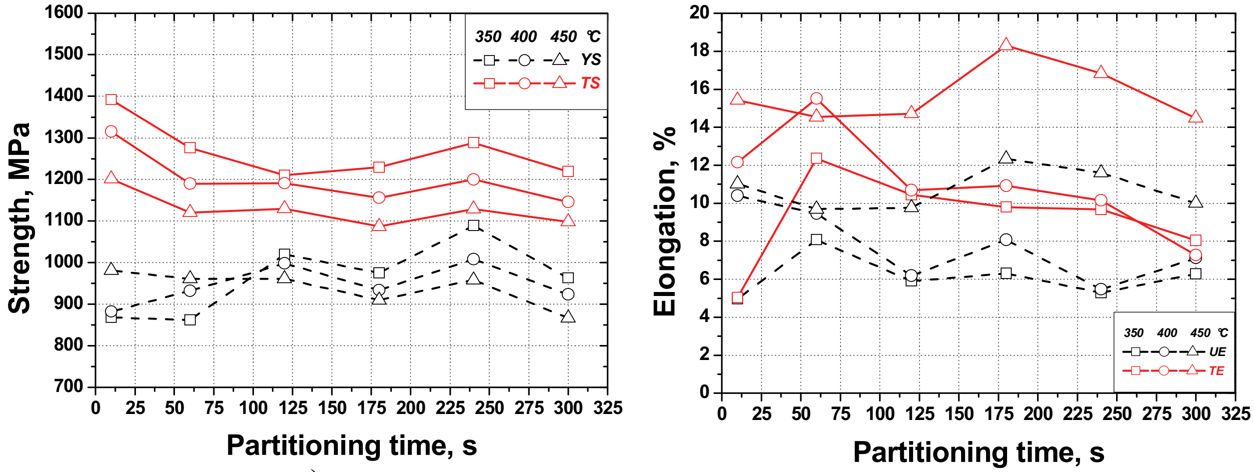


Figure 2 Retained austenite fractions ($f\gamma_{ret}$) obtained by Q&P heat treating following full austenitization reflecting the effect of: a) carbon content in CMnSi alloys, b) partial replacement of Si by Al c) Mo alloying of a CMnSi grade d) Mo addition to a CMnAl grade [8].

Tensile Properties Obtained by Quenching and Partitioning

Tensile Properties obtained for a CMnSi Q&P grade

The tensile properties obtained after full austenitization and Q&P heat treating of the CMnSi grade are given in Figure 3 as a function of partitioning time for three partitioning temperatures. Tensile strengths range from 1100 to 1390 MPa and decrease with increased partitioning temperature with a significant drop at short partitioning times (Pt ≤ 60 s). Yield strengths vary from 860 to 1090 MPa. The effect of partitioning time on yield strength is less pronounced, an increase is apparent with increased holding at the partitioning temperature. The lowest partitioning temperature seems to result in the highest yield strength levels although the data show significant scatter. Total elongations range from 5 to 18 % whereas uniform elongations range from 5 to 12 %. An increase in partitioning temperature results in higher elongations (uniform and total), especially for 450 °C.



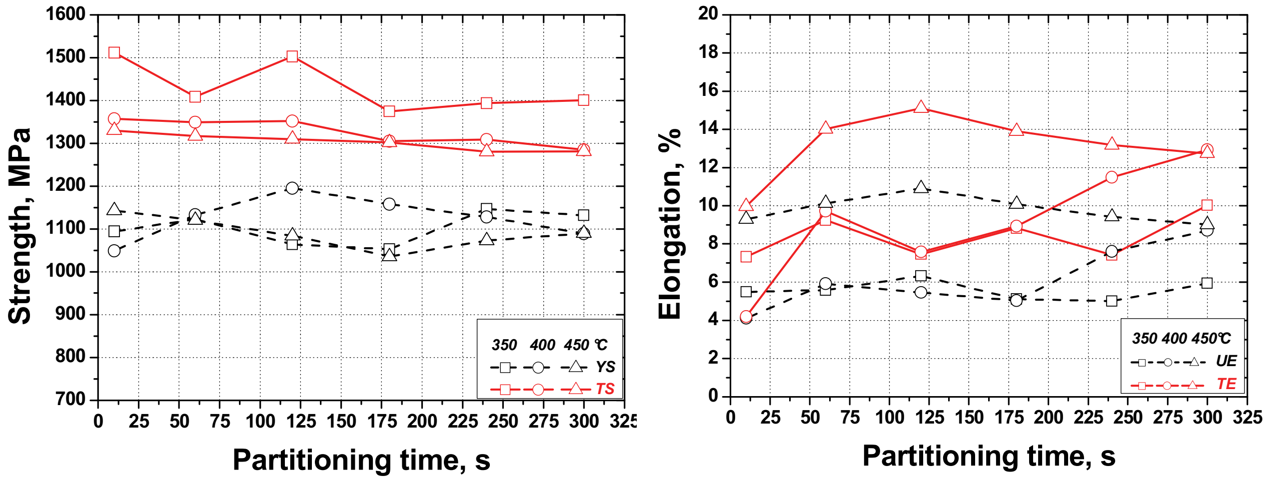
a) b)

Figure 3 Tensile properties of Q&P heat treated CMnSi samples as a function of partitioning time for partitioning temperatures 350, 400 and 450 °C: a) Yield (YS, dashed line) and tensile (TS, solid line) strength and b) uniform (UE, dashed line) and total (TE, solid line) elongation.

Effect of Mo and Al Alloying on Tensile Properties Obtained by Q&P

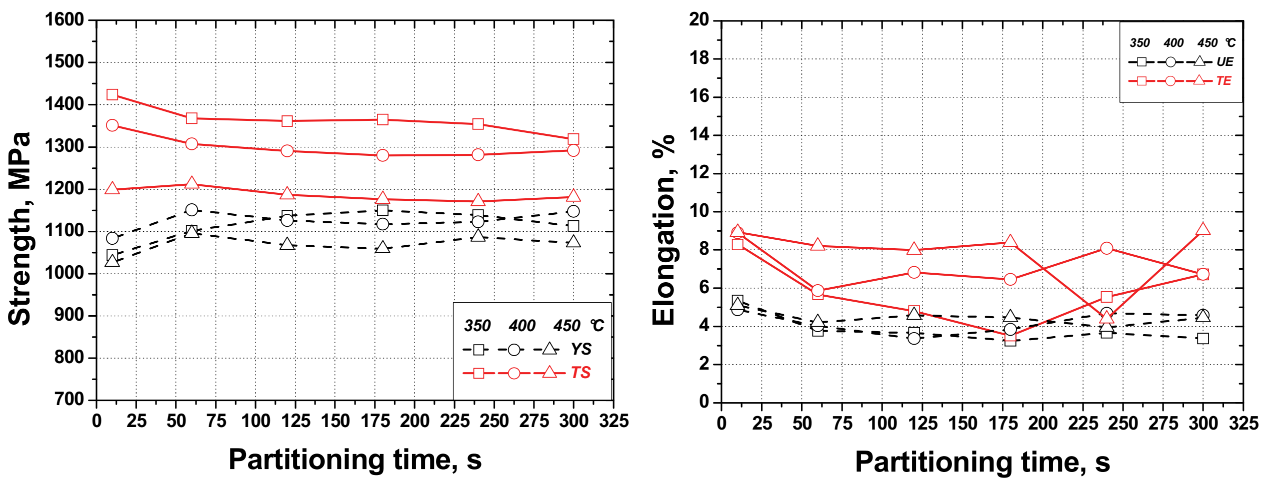
The mechanical properties obtained for the MoCMnSi grade obtained by Q&P processing following full austenitization are shown in Figure 4. These data reflect the effect of a Mo addition to the CMnSi grade when compared to the properties shown in Figure 3. Tensile strengths of 1280-1510 MPa and yield strengths of 1050-1200 MPa are obtained with uniform elongations of 4-11 % and total elongations of 4-15 %. In general, higher yield and tensile strengths are obtained for the MoCMnSi grade than for the CMnSi alloy. Similar trends are observed for the tensile strength, namely a decrease with increasing partitioning temperature. No consistent trend with temperature or time is observed for the yield strength. Higher yield strength is obtained for this alloy compared to the CMnSi grade. A significant improvement in elongation is obtained especially given the higher strength levels. The highest partitioning temperature results again in the highest ductility levels.

The tensile properties obtained for the MoCMnAl grade are given in Figure 5. Tensile strengths of 1170-1420 MPa and yield strengths of 1030-1150 MPa are obtained with total elongations of 4-9 % and uniform elongations of 3-5 %. Similar strength level trends with partitioning conditions are again obtained. Although this grade contains negligible silicon levels, higher yield strengths are obtained compared to the levels obtained in the CMnSi alloy. This may be related to the higher carbon concentration. It is interesting to note that the Al-grade containing the lowest retained austenite fractions exhibits the lowest ductility levels whereas the highest combinations of strength and ductility are obtained for the Mo-grade with the greatest amount of stabilized austenite.



a) b)

Figure 4 Tensile properties of Q&P heat treated MoCMnSi samples as a function of partitioning time for partitioning temperatures 350, 400 and 450 °C: a) Yield (YS, dashed line) and tensile (TS, solid line) strength and b) uniform (UE, dashed line) and total (TE, solid line) elongation.



a) b)

Figure 5 Tensile properties of Q&P heat treated MoCMnAl samples as a function of partitioning time for partitioning temperatures 350, 400 and 450 °C: a) Yield (YS, dashed line) and tensile (TS, solid line) strength and b) uniform (UE, dashed line) and total (TE, solid line) elongation.

The tensile properties reported in Figure 3, 4 and 5 are summarized in Figure 6 on a total elongation versus tensile strength diagram. Also shown in Figure 6 are the tensile properties obtained for the CMnSi and CMnAlSi grades. The limited amount of material available of these grades did not enable a study similar to the one presented in Figures 3-5. Heat treating was performed at only one (300 °C for the CMnAlSi alloy) or two (300 and 400 °C for the CMnSi alloy) partitioning temperatures for 10 to 900 s. Higher strength levels are obtained for these grades presumably due to their higher carbon contents. Shown by the dashed line in Figure 6 is the plot of the predicted elongation/strength evolution of martensite/austenite mixtures according to the model proposed by Matlock *et al.* [1,2]. It should be recognized that although the model assumes a particular martensite and austenite having particular phase properties, it seems to provide an upper bound for the experimental results. It should be recognized that decarburized or "partitioned" martensite is likely to be softer than as-quenched martensite, so it is not surprising that the Q&P properties are below the values predicted for α_M/γ mixtures. Comparing the data shown in Figure 6 with the "third generation AHSS" property field identified in Figure 1 indicates that properties of the "third generation" can be obtained by the Q&P heat treatment.

As can be seen from Figures 3-6, an increase in partitioning temperature results in a tensile strength decrease and in general in an increased total elongation. However, the extent of these changes seems to be composition dependent. In this way, increasing the partitioning temperature results in a more limited increase in elongation for the MoCMnAl grade in contrast to the increase observed for the MoCMnSi and CMnSi samples.

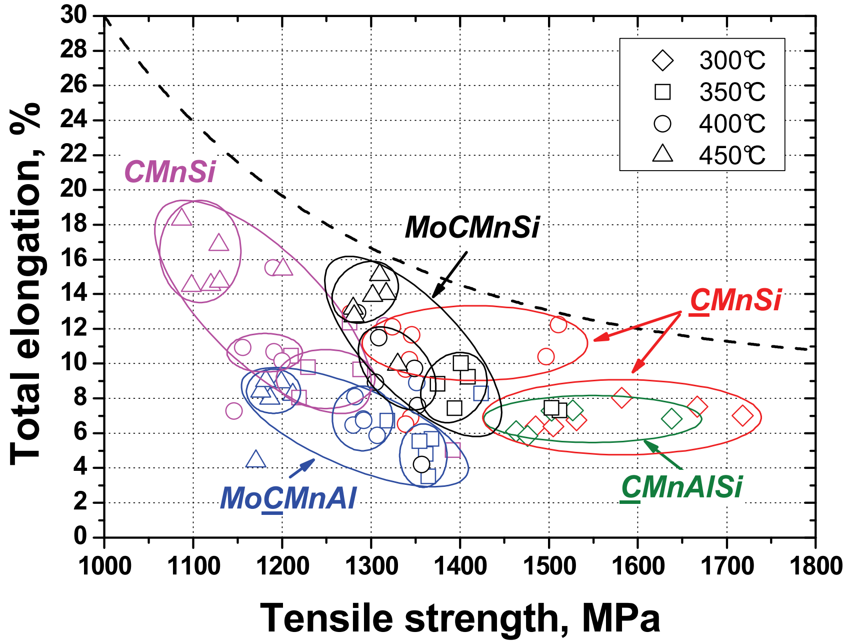


Figure 6 Total elongation versus tensile strength diagram obtained via Q&P for different compositions following full austenitization. The dashed line corresponds to calculations according to the model proposed by Matlock [1,2] for mixed martensite/austenite microstructures.

It has been reported previously that the strain hardening of Q&P steels depends on the partitioning conditions applied [4,7,9]. The TRIP effect has been shown to operate and contribute to strain hardening in Q&P steels [9]. The influence of partitioning conditions on strain hardening is likely related to the overall strength level, mechanical stability of the austenite, carbon content and thus also strength of the martensite, precipitation in the martensite, etc. Figure 7 shows the stress-strain and instantaneous strain hardening or n-value behavior as defined by

$$n - value = \frac{\partial \ln \sigma}{\partial \ln \varepsilon} \approx \frac{\ln \sigma_2 - \ln \sigma_1}{\ln \varepsilon_2 - \ln \varepsilon_1} \quad (1)$$

plotted as a function of true strain for a short (10s) partitioning treatment at a low temperature (350 °C) and a longer (300 s) treatment at a higher temperature (450 °C) for the CMnSi, MoCMnSi and MoCMnAl grades.

Clearly different strain hardening is obtained for the two partitioning conditions. Partitioning at 350 °C for 10 s results in continuously decreasing strain hardening with increased strain. Fairly similar strain hardening behavior is observed for all grades. The CMnSi grade has a lower yield strength and slightly higher strain hardening. However, for all grades continuously decreasing instantaneous strain hardening with true strain is observed. This trend is fairly similar to the strain hardening of quench and tempered steels [10]. Significantly different trends are observed for the longer partitioning time and higher temperature as shown in Figure 7c and d. The tensile strength levels are about 200 MPa lower than the ones obtained after partitioning at 350 °C for 10 s. The CMnSi and MoCMnSi grades containing high volume fractions of retained austenite (Figure 2) exhibit increasing strain hardening with increasing true strain characteristic of TRIP type strain hardening [9]. The highest n-values are obtained for the CMnSi grade. Note however, that the strength level in this grade is lower by about 200 MPa compared to the MoCMnSi grade. Clearly lower strain hardening is exhibited by the MoCMnAl steel containing a very low amount of retained austenite. Yielding occurs at a similar strength level as the MoCMnSi steel.

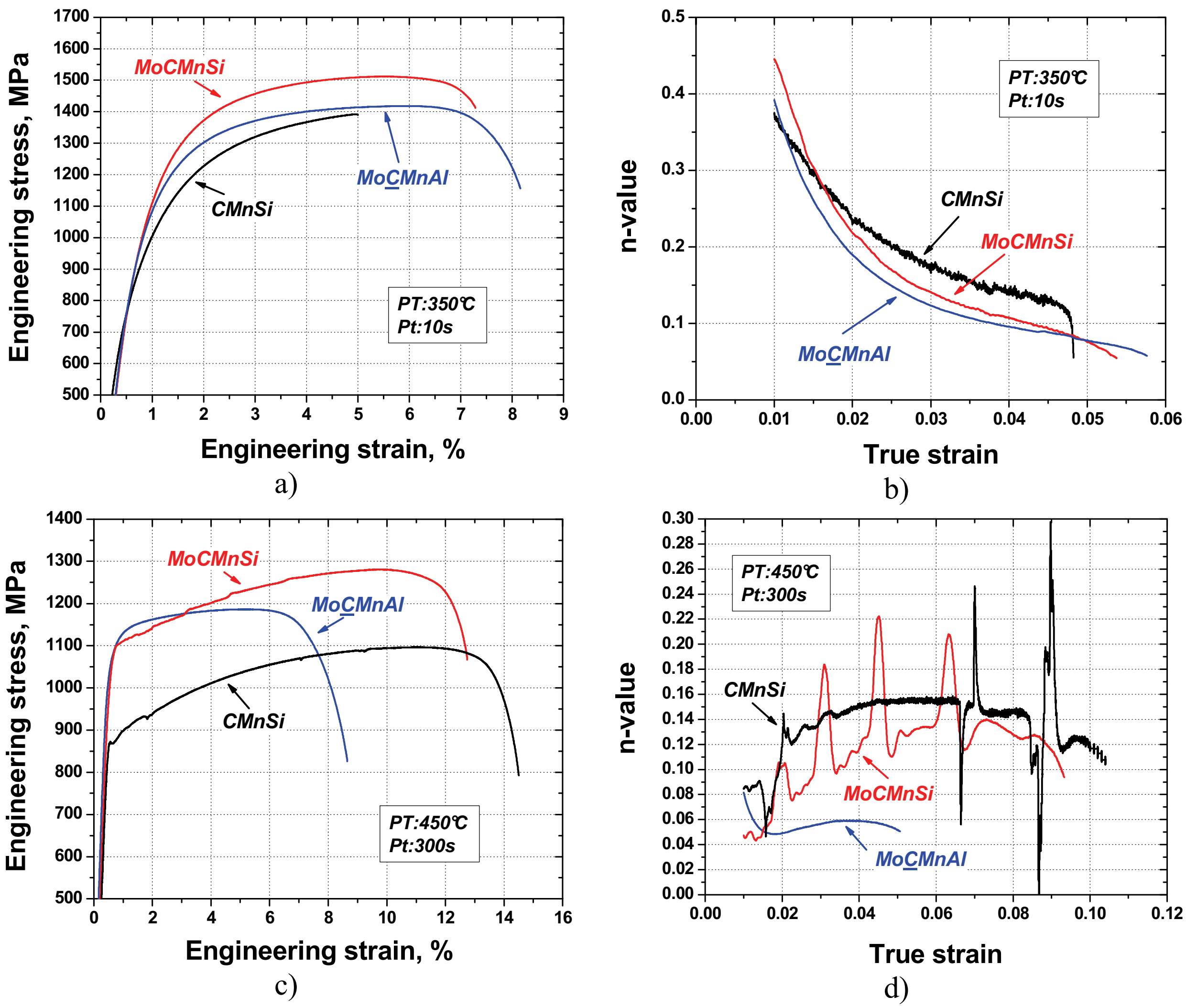


Figure 7 Stress-strain curves and instantaneous strain hardening versus true strain obtained for the CMnSi, MoCMnSi and MoCMnAl Q&P grades for partitioning done at 350 °C for 10 s (a and b) and 450 °C for 300 s (c and d).

These results indicate that the retained austenite stabilized at longer partitioning times and/or higher partitioning temperatures (in combination with somewhat lower strength levels), contributes effectively to increasing strain hardening with strain, and to ductility. Alloying to enhance ductility should hence focus on stabilizing retained austenite volume fractions.

Conclusions

Quenching and Partitioning was studied as a potential way to obtain "third generation AHSS" mechanical properties. A variety of steel compositions were used with alloying modifications involving Si, Al and Mo. It was shown that the highest retained austenite fractions were stabilized in the MoCMnSi grade. Partial replacement of Si by Al resulted in significantly lower retained austenite fractions. Novel tensile properties were obtained filling a gap in the strength/elongation diagram. The stress-strain curves and strain hardening behavior exhibit a dependence on partitioning conditions. The most effective contribution of the TRIP mechanism to an increased strain hardening is obtained for longer partitioning times and/or higher partitioning temperatures in the steels examined. This leads to enhanced properties for these conditions in the MoCMnSi grade. The Al alloyed grade exhibits the lowest instantaneous strain hardening and ductility levels.

Acknowledgements

The Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen) is gratefully acknowledged for funding this research. The authors also gratefully acknowledge the support of the sponsors of the Advanced Steel Processing and Products Research Center, an industry/university cooperative research center at the Colorado School of Mines.

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