

Quench and Partitioning Heat Treatment to Improve the Ductility of Ultra High Strength Steel

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Abstract

Quench & Partitioning (Q&P) heat treatment was carried out on an ultra high strength steel with the Q&P temperatures below the Ms-Temperature. It was found that by increasing the single stage Q&P temperature resulted in decrease in yield strength, ultimate tensile strength and hardness with marginal increase in the total elongation of the steel where no retained austenite is found. With the double stage Q&P heat treatment a very marginal decrease in the ultimate tensile strength found with a significant increase in its total elongation due to presence of 3-5% retained austenite detected by XRD. Hence, double stage Q&P heat treatment can be an effective method to improve the ductility of ultra high strength steels by stabilizing the retained austenite which give the TRIP effect while deformation.

Keywords: quench and partitioning, ultra high strength steel, improved ductility, microstructure

1. Introduction

Quench and partitioning (Q&P) steels have similar chemical composition to TRIP assisted steels with the excellent combination of strength and elongation suitable for automotive applications. In this process the steel is subjected to quenching in a temperature range below the martensite start temperature after austenitization above A_3 temperature or after inter critical annealing, the steel may be either held at the same quenching temperature called as single stage Q&P or the steel temperature is raised above the quench temperature either in the martensite regime or above the martensite regime to the bainitic regime followed by water quenching or air cooling called as second stage Q&P to achieve attractive level of strength and elongations in the third generation AHSS regime suitable for automotive applications (David K Matlock et al., 2003; Hana Jirkova et al., 2012; Wang Li et al., 2013; G. A. Thomas & J. G. Speer, 2014; Yuki Toji et al., 2014; Emmanuel De Moor et al., 2017; Li, Z. et al., 2021; Y.Y. Cheng et al., 2022; Xu, Y. et al., 2022; Yuki Toji et al., 2023; Christian Illgen et al., 2023; Evgeniy Tkachev et al., 2023; Pengsheng Hu et al., 2023; Roman Mishnev et al., 2023). In the process of partitioning the carbon from the martensite is rejected to the surrounding to become relatively soft martensite whereas the rejected carbon is captured by the retained austenite to stabilize at room temperature. Various alloying elements play a vital role in the carbon partitioning and stabilizing the retained austenite in addition to the grain refinement and morphological changes in the microstructure to give the unique characteristics microstructure and mechanical properties to the steel. Effect of C & Mn-Carbon and Mn stabilizes the retained austenite in the Q&P steel also imparts the morphology of the microstructure in the steel (Huan Xiao et al., 2022; Emmanuel De Moor et al., 2011). Effect of Si suppresses the cementite and carbide formation leading to availability of more rejected/partitioned carbon from the martensite to the retained austenite to stabilize it (S Jenicek et al., 2017). Effect of Cr & Mo and V-Q&P heat treatments in Cr-Mo steel with less Si and Al elements presents an obvious characteristic of tempered martensite, while high-Silicon and high-aluminum steels with more Si or Al contain more residual austenite and Cr, Mo, V further gives more stable austenite (Wen-hua Xu et al., 2023; Roman A. Kussa et al., 2022). Effect of Nb & Ti-grain boundary pinning by precipitates and Nb solute

drag effects refine the austenite grain size during the hot-rolling process to give refined in the final microstructure of Q&P steel. The remaining supersaturated Nb suppresses the bainite formation and decreases the final bainite fraction formed in the Q&P process. Ti too helps in grain refinement by the precipitation of fine carbides and carbo nitrides (Zhisong Chai et al., 2021; Ji Dong et al., 2017).

Effect of Cu-Combination of nanosized Cu-rich precipitates and ultrafine microstructure through the addition of Cu can be a highly potential method to improve the mechanical properties of Q&P steel (Xu Wang et al., 2022).

2. Experimental

The steel used in the present study was designed and induction melted followed by hot deformation to 70mm*70mm billet size to further processing. The chemical composition of the steel was obtained using SPECTRO optical emission spectroscopy. The hot deformed billet was then sliced to 2mm thick sheets in an EDM machine for the further experiments. JMat Pro software was used to construct the CCT diagram and the critical temperatures such as A₃, A₁, B_s and M_s and found to be 843, 743, 498 and 328°C respectively. The experiment involved holding the samples above A₃ temperature for 5 min followed by quenching at 150, 200, 250°C for 5min for the single stage Q&P and the 200 and 250°C samples were again partitioned at 300°C for 5min for the double stage Q&P and then water quenched. The heat-treated samples were then subjected to standard metallography for microstructural observation using a Hitachi scanning electron microscope (SEM). Subsize standard (ASTM E8) tensile specimens were made from the as-hot-deformed and heat-treated samples for the tensile test on a Zwick/Roell make 250 kN universal tensile testing machine at a standard strain rate of 0.008/s for the evaluation of mechanical properties.

3. Results and Discussion

Chemical composition of the steel obtained through OES is shown in Table 1. The steel is having (Wt. %) 0.2C-2Mn-1.7Si-0.9Cr-0.18Mo-0.07Nb-0.04Ti-0.2Cu-0.05Ni-0.025Al-0.002B-0.04S-0.06P. The steel is a low carbon low alloy steel suitable for automotive applications. C and Mn stabilizes the retained austenite in the steel whereas Si helps in retarding the cementite formation leading to additional austenite stabilization. Cr, Mo and V give strength to the steel and Nb, Ti with the fine precipitates helps in grain refinement in the steel. The Cu with the nano size precipitate further improves the strength of the steel.

Table 1. Chemical composition of the steel (wt. %)

C	Mn	S	P	Si	Al	Cr	Ni	Cu	Nb	V	Ti	Mo	B
0.213	2.07	0.037	0.056	1.71	0.025	0.899	0.045	0.213	0.069	0.005	0.038	0.176	0.0017

The CCT diagram of steel with the critical temperatures and heat treatment cycle is shown in Figure 1.

CCT

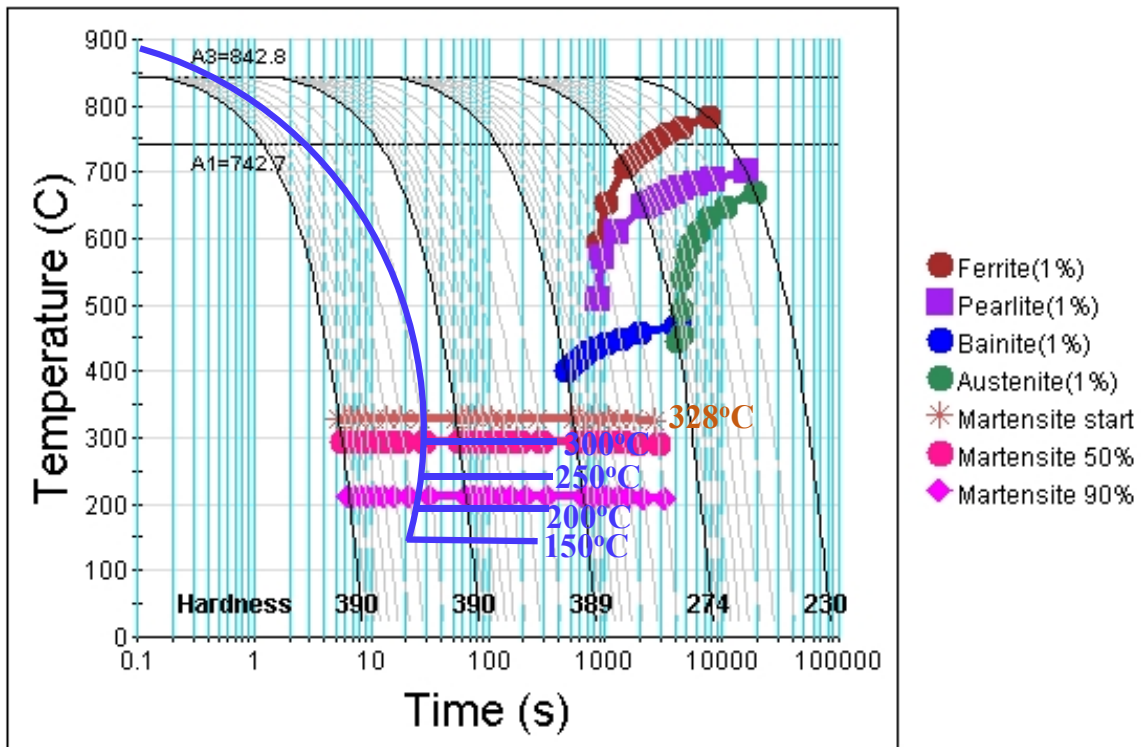


Figure 1. CCT diagram of the steel with the critical temperature and heat treatment cycle

The low and high magnification SEM micrograph of the steel austenitized at 880°C followed by salt bath quenching and partitioning at 150, 200 and 250°C and then water quenched is shown in Figure 2. The volume fraction of martensite at each quenched temperature can be evaluated through Koistinen-Marburger empirical equation.

$$f = 1 - \exp[-0.011 (M_s - T)] \dots\dots\dots (1)$$

For the present steel $M_s = 327.9^\circ\text{C}$. Hence, the volume fraction of martensite

For 150°C, $f = 0.86$

For 200°C, $f = 0.75$

For 250°C, $f = 0.58$

Hence, the volume fraction of martensite at the temperature of 150, 200 and 250°C are 86%, 75% and 58% respectively.

The stress-strain diagram of the single stage and double stage quench and partitioning steel is shown in Figure 3. The change in mechanical properties of the steel with increase in quench and partitioning temperature is shown in Figure 4. The yield strength (YS), ultimate tensile strength (UTS) and hardness (HV) were found to decrease with a marginal increase in the total elongation of the steel with the increase in Q&P temperature. With an increase in Q&P temperature, the volume fraction of martensite decreased, which led to a decrease in strength and hardness, with a marginal increase in the total elongation of the steel.

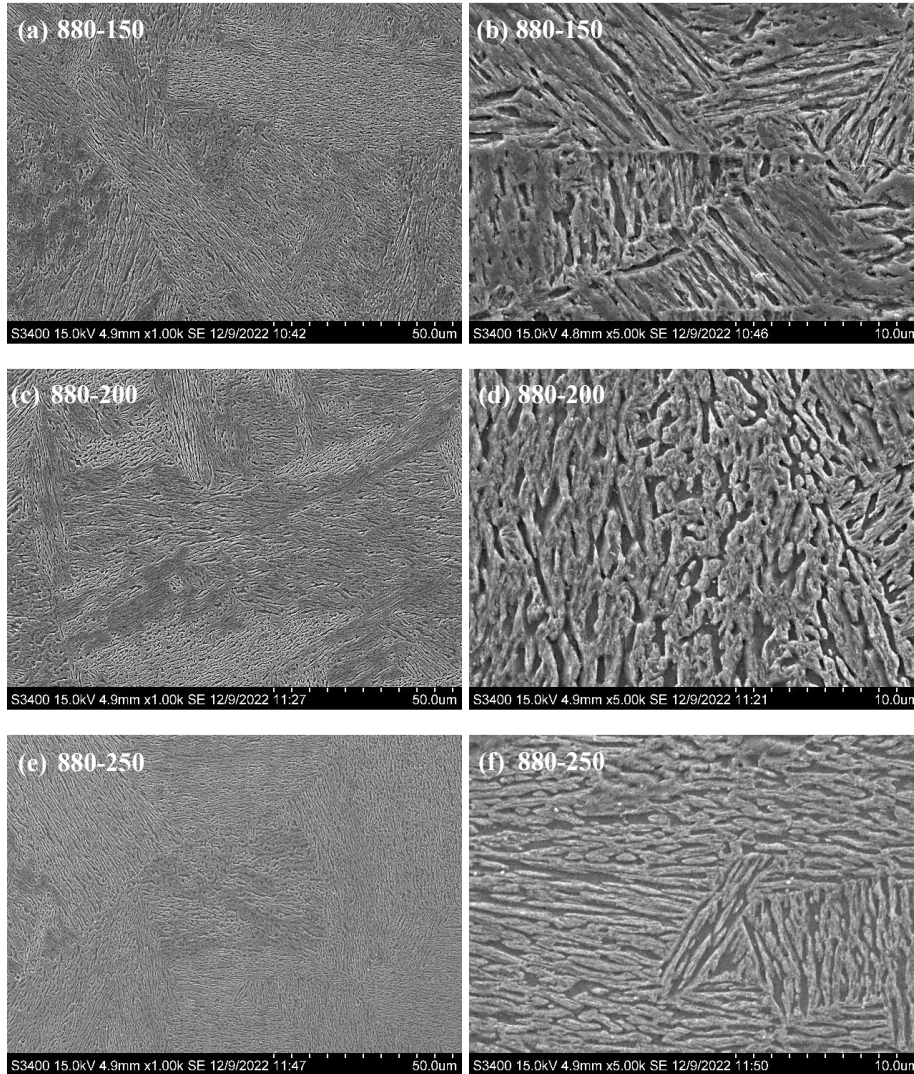


Figure 2. SEM micrograph of the steel at low magnification (a), (c) and (e) and their corresponding high magnification micrographs (b), (d) and (f) of the single stage quenched and partitioning temperature 150, 200 and 250°C respectively

The SEM micrograph of the steel at low and high magnification subjected to double stage Q&P at 300°C after quenched at 200 and 250°C is shown in Figure 5. The mechanical properties of the steel after partitioning at 300°C compared to their single stage quench and partitioning condition at 200 and 250°C mechanical properties is shown in Figure 6. The results clearly show that a marginal decrease in the ultimate tensile strength and a significant increase in the total elongation occurs due to the double stage quench and partitioning of carbon from the martensites. The XRD of the Q&P steels is shown in Figure 7. The retained austenite content of the steel is summarized in Table 2. It can be observed that no retained austenite is detected in the single stage Q&P, which might be due to the transformation of the retained austenite to bainite/martensite during cooling, whereas a maximum of 5% retained austenite is found at 200°C–300°C double stage Q&P and with 250°C–300°C it is further decreased to 3%. The partitioning of carbon resulted in soft martensite and enrichment of retained austenite, which helps in the TRIP effect to give adequate strength and elongation to the steel.

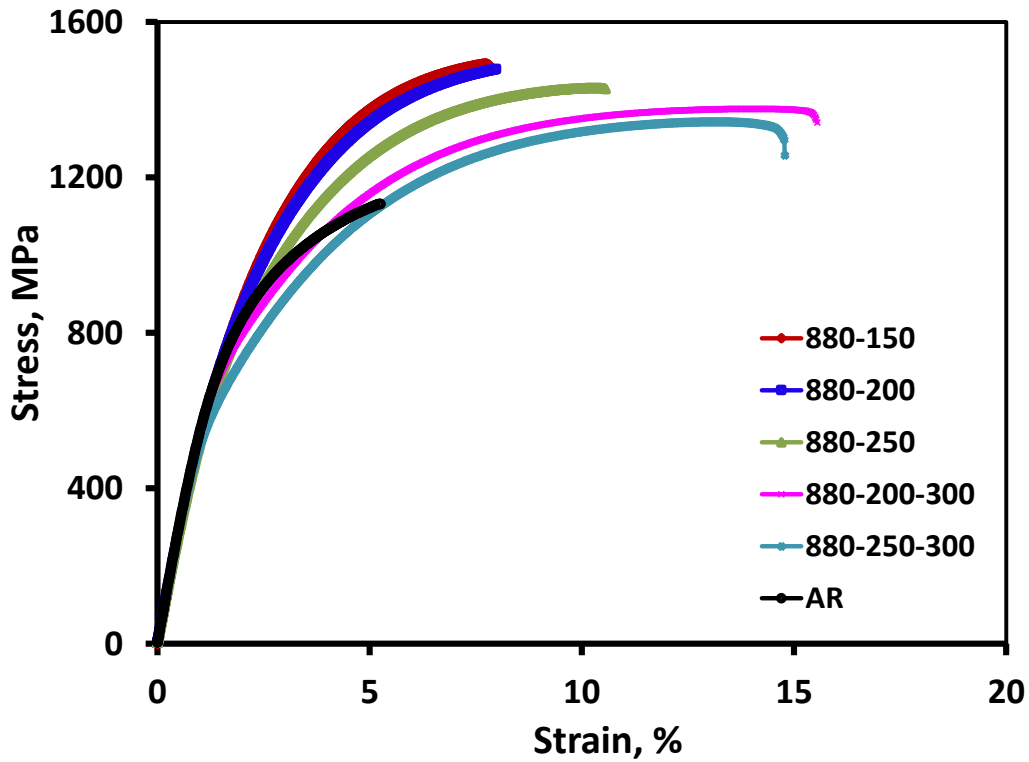


Figure 3. Stress-strain diagram of the quenched and quenched and partitioned steel

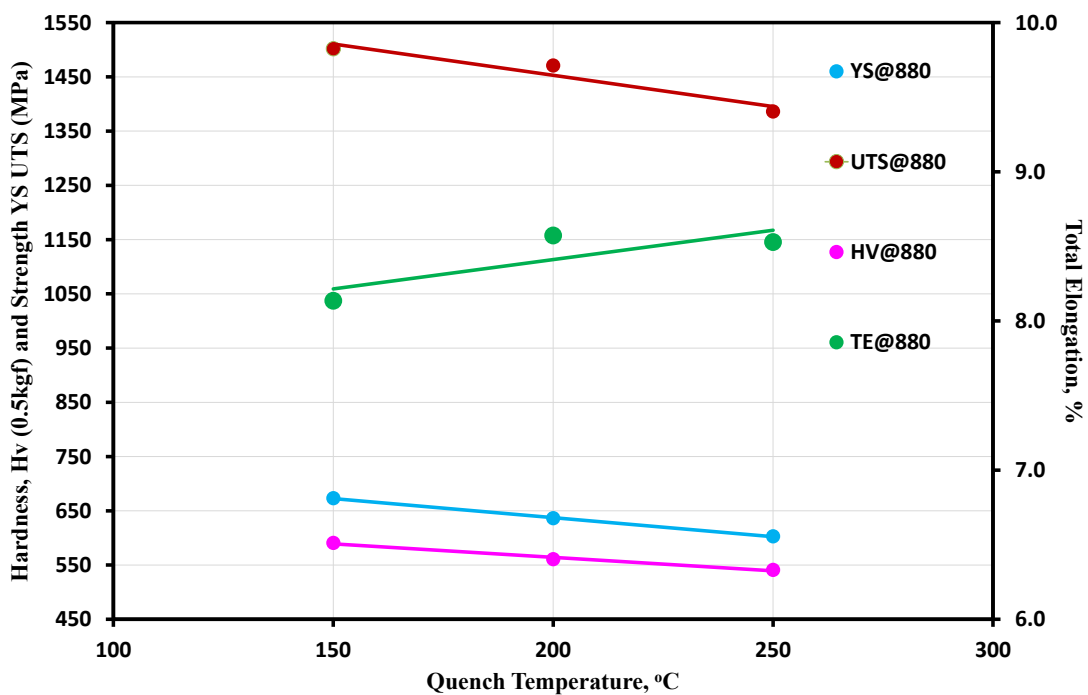


Figure 4. Change in yield strength (YS), ultimate tensile strength (UTS), hardness (Hv) and total elongation (TE) of the steel with increase in quenching temperature

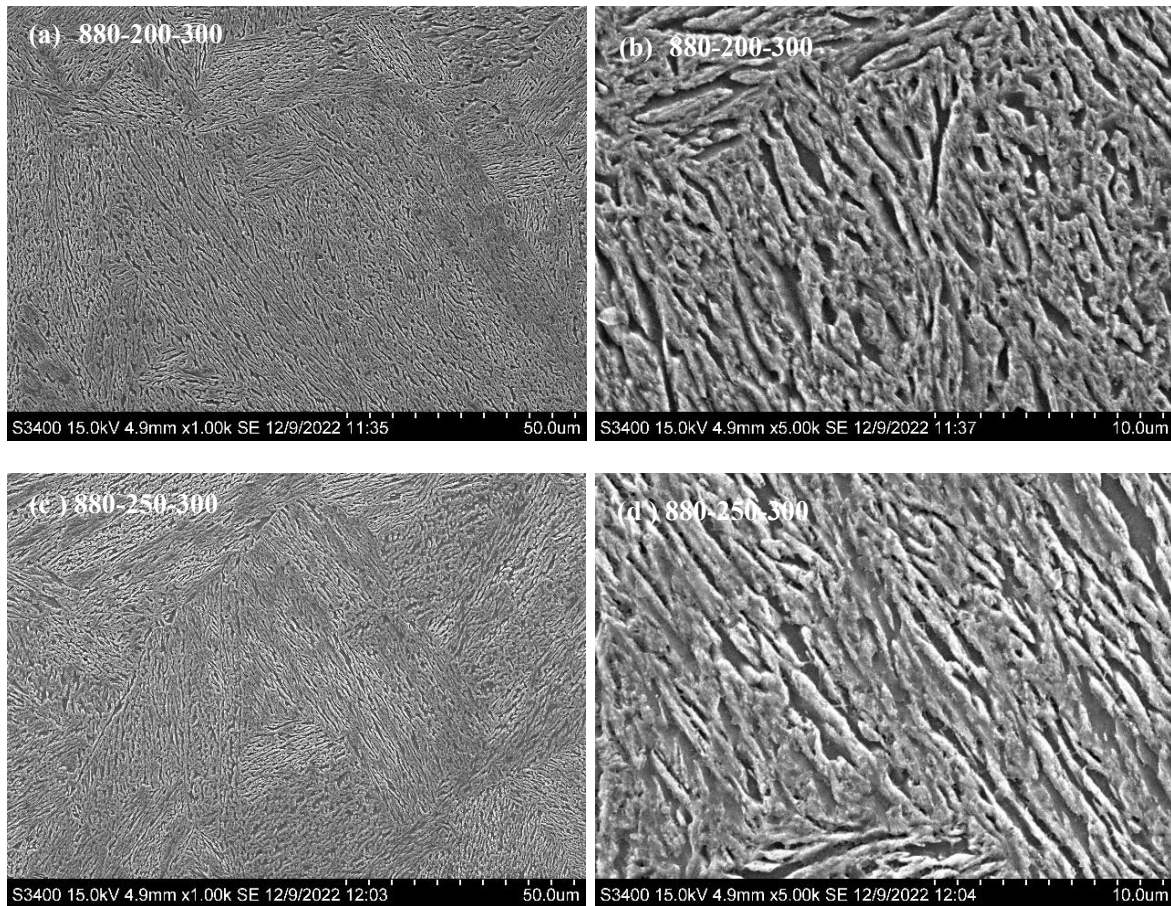


Figure 5. Low and high SEM micrograph of the steel subjected to double stage quench and partitioning at 300°C after quenching at 200°C (a) & (b) and after quenching at 250°C (c) & (d)

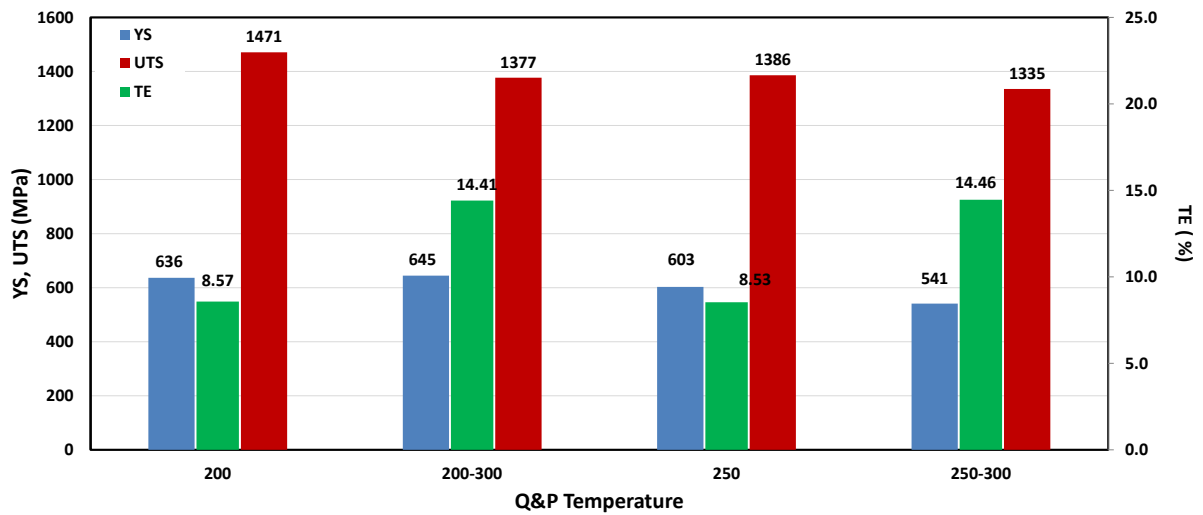


Figure 6. Change in mechanical properties of the steel after partitioning compared to the only quenched condition

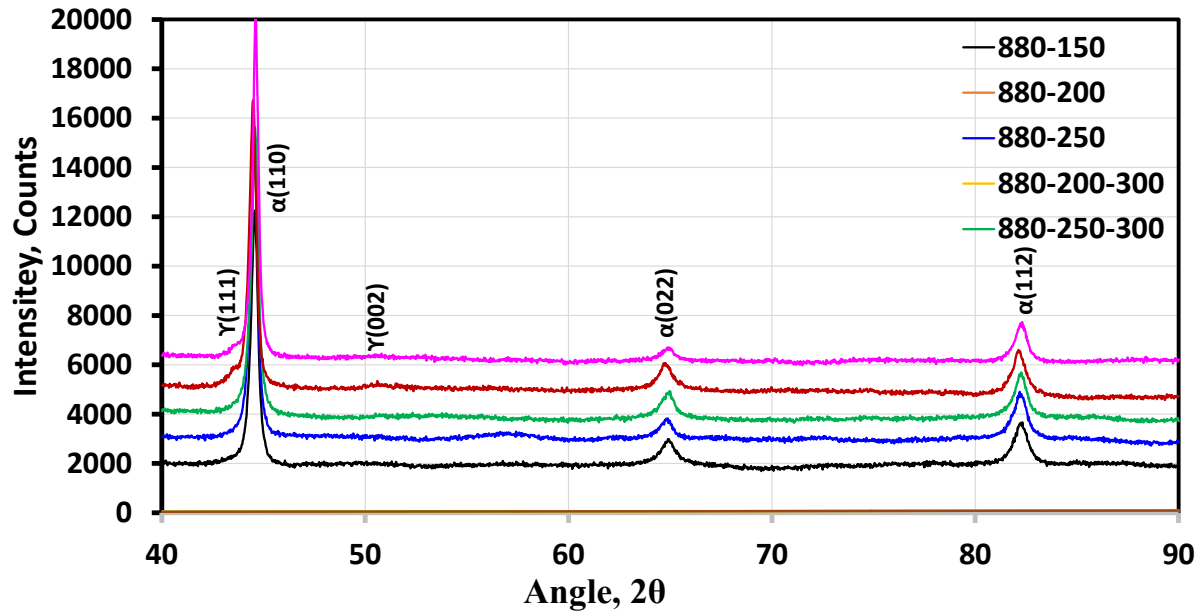


Figure 7. XRD analysis of retained austenite volume fraction of the Q&P steels

Table 2. Retained austenite content evaluated through XRD

Q&P Condition	Retained Austenite, %
880°C-150 °C	0
880 °C -200 °C	0
880 °C -250 °C	0
880 °C -200-300 °C	4.95
880 °C -250 °C -300 °C	3.34

4. Conclusions

Single stage Q&P at 150, 200 and 250°C although give ultra high strength >1350MPa, poor elongation was found due to absence of retained austenite content. With increase in single stage Q&P temperature the UTS decreased marginally with small increase in the total elongation due to carbon partitioning in the steel.

Significant improve in the total elongation was found with a marginal decrease in the ultimate tensile strength by the double stage Q&P of the steel at 300°C which were subjected to single stage Q&P at 200 and 250°C due to presence of 3-5% retained austenite. More studies under progress to further improve the properties by double stage Q&P heat treatment cycle.

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