Influence of tempering Temperature on Fatigue and Mechanical Properties of High Strength Steel

Hyuksun Kwon, Younil Chung

Abstract

The present study evaluates the mechanical and fatigue properties of HPF steel through the QT heat treatment with quenching process with respect to the variation of tempering temperature. Tensile, hardness and fatigue tests were performed at room temperature. As tempering temperature increases, the tensile strength and Vickers hardness values decrease, while the total elongation increases. The increasing rate of elongation in the tempering range 200~350°C is higher than the ones in other tempering ranges, though the tensile strength decreases similarly. In this study, it is observed that the HPF steel tempered at 250°C shows the best result in the low cycle fatigue test.

Introduction

In the automotive industry, there has been a continuing trend toward the weight reduction of vehicles in response to the need for cost savings, fuel efficiency, and reduction in CO_2 emissions. Considerable efforts have been made to reduce thickness of components without significant loss of their stiffness and fatigue properties, and AHSS is being increasingly used for the automotive chassis components. The QT(quenching and tempering) heat treatment is a technique to produce high strength steel with the martensite microstructure by heating steel over the high temperature of 900°C and then forming components and cooling them rapidly. However, components produced through the QT method tend to have low fatigue properties, while having high strength, due to their low elongation. But proper tempering treatment can effectively improve fatigue properties of AHSS by securing its high elongation, though it may cause relatively negligible or tolerable loss of strength.

Extensive studies have been carried out to improve the fatigue strength of various kinds of steels through effective tempering process [1-3]. Fatigue properties with boron and Cr-Mo steels were investigated with the boron effects of the austenite grain size [4]. The austempering effects of various kinds of hot forged steels were investigated and volume fractions of phase were the main effect in the fracture toughness [5]. The austemped ductile irons with low and high cycle tests were found and morphology of retained austenite were discussed [6-7]. The medium carbon steel had a various microstructures through the QT, air-cooling and step cooling and ferrite-bainite steel was stronger than other microstructure [8]. Crack propagation properties of low alloy steel was found and reported that crack threshold were increased when tempered at 370°C for 2h [9]. The B and Si effects of 4320 steel was discussed that Si reduced the fatigue performance with the grain growth [10] and works on ferrous martensite tempering phenomena including various carbide formations are recently understood [11]. The most important factor in tempering is the tempering temperature. Low tempering temperature and short tempering time has little effect on the fatigue strength due to its little effect on the strength and elongation, whereas excessive temperature and time in tempering weakens the strength of high strength steels and thereby yields lower fatigue strength. Thus, to secure the desired fatigue strength, it is crucial to evaluate optical conditions of tempering for the high strength steel. In this study, low cycle fatigue behavior of STAB and HPF steels, which are widely used as sheet materials in automotive chassis systems, is investigated in different conditions of tempering temperature.

Material and test method

Chemical compositions of STAB which was conventional steel and HPF steel used in this study are presented in Table 1 and Table 2 respectively. In view of the alloy design, Mn of HPF steel is an element related to the lowering of austenitizing temperature, fine graining and hardenability. N and Ti can affect the bake hardening for high yield strength. Heat treatment conditions are presented in Fig. 1. As shown in Fig. 1, the steel was quenched at the cooling rate of 950°C/15sec. The tempering treatment was done for 30 minutes. Specimens of STAB steel were tempered at 340°C, and specimens of HPF steel were tempered at 100, 200, 250, 300, 340 and 400°C in the case of tensile tests and tempered at 100, 250, and 340°C for fatigue tests.

C (wt.%)	Si (wt.%)	Mn (wt.%)	P (wt.%)	S (wt.%)	S.Al (wt.%)	Ti (wt.%)	Ni (wt.%)	B (ppm)
0.16~0.23	0.10~0.25	0.30~0.60	< 0.025	< 0.015	<0.06	-	0.1~0.3	10~50

Table 1 Chemical composition of STAB steel

C (wt.%)	Si (wt.%)	Mn (wt.%)	P (wt.%)	S (wt.%)	S.Al (wt.%)	Ti (wt.%)	W (wt.%)	B (ppm)	N (ppm)
0.23~0.25	0.20~0.30	1.60~1.70	<0.017	<0.007	0.02~0.05	0.02~0.03	0.02~0.04	10~20	100~160

Table 2 Chemical composition of HPF steel

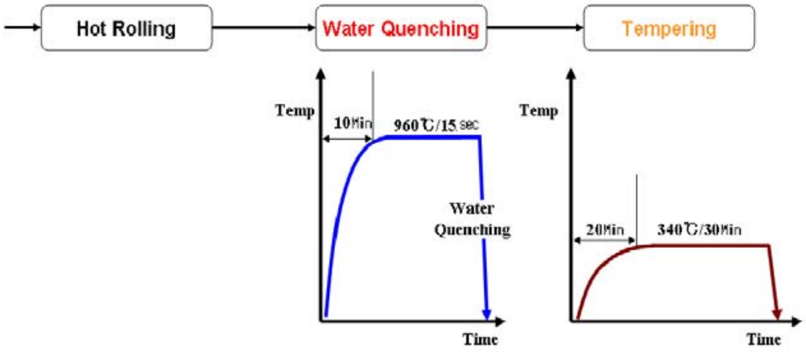


Fig. 1 Quenching & tempering treatment process of test specimens

The tensile tests were performed at room temperature using a 60 tons ZWICK testing machine and the specimens were standardized by the JIS 5 as shown in Fig. 2. The gage length was 50mm and the tests were done in accordance with the JIS Z 2241 standard. The hardness tests were conducted using the Vickers method.

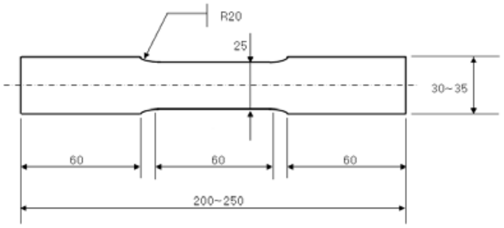


Fig. 2 Specimen configuration for tensile test

The low cycle fatigue tests were performed at room temperature according to ISO standard 12106 [12]. The main fatigue test range was between 10^3 and 10^5 cycles. The applied frequency was 0.2 Hz and the strain amplitude ranged between ±0.1 ~ ±0.7%. The failure criterion was 25% load drop. The alignment setting for anti-buckling in the tension and compression loading was within class 2.

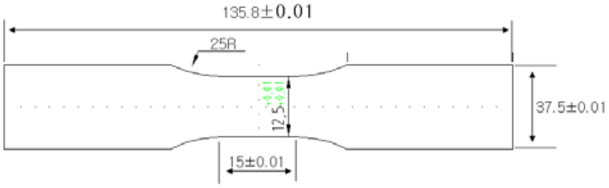


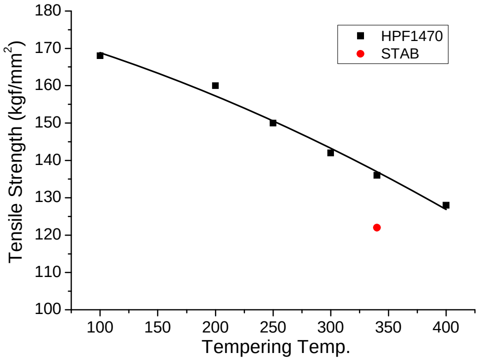
Fig. 3 Specimen configuration for low cycle fatigue test

Test results and discussion

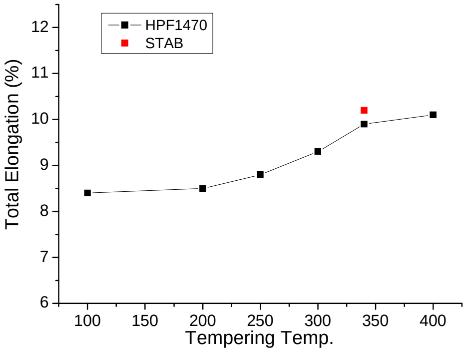
Fig. 4 shows how tensile strength and elongation vary with tempering temperature. As tempering temperature increases, the tensile strength descends continuously while the elongation increases. More specifically, in the tempering range 100~250°C, the drop of tensile strength was significant, but the increase of elongation was comparatively small. In the range of 250~340°C, the elongation increases considerably as tensile strength decreases. In the range above 340°C, the increment of elongation is not substantial as compared to the decrease of tensile strength. The decomposition of the retained austenite at higher tempering temperature can result in the formation of carbides, leading to embrittlement. This phenomenon is referred to as tempered martenstie embrittlement (TME). When tempered at 340°C, HPF steel has higher strength by 14kgf/mm^2 as compared with STAB steel, while the difference of elongation is merely 0.3%.

In the fatigue field, in general, high elongation steels are more beneficial in the region of short fatigue life, while high tensile strength steels have more advantages in the long life region.

Fig. 5(a) shows hardness variation with tempering temperature. Vickers hardness decreases as tempering temperature increases. It can be seen that at the tempering temperature 340°C, HPF steel has higher hardness by 30 HV than STAB steel. Fig. 5(b) shows the linear relationship between tensile strength and hardness. The tensile strength increases with hardness at the rate of 0.51 kgf/mm^2 per 1 HV.

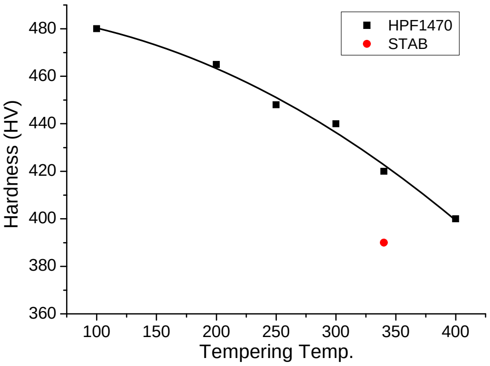


(a) Tensile strength vs. tempering temperature

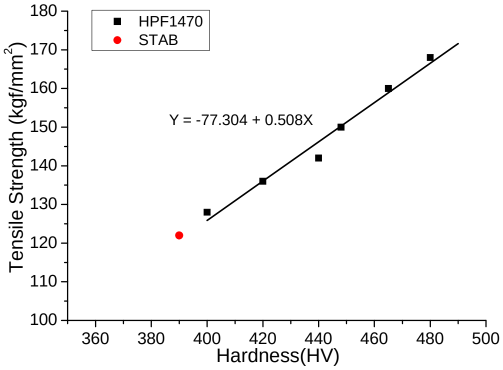


(b) Total elongation vs. tempering temperature

Fig. 4 Variation of tensile properties with tempering temperature



(a) Vickers hardness vs. tempering temperature



(b) Tensile strength vs. Vickers hardness

Fig. 5 Vickers hardness test result

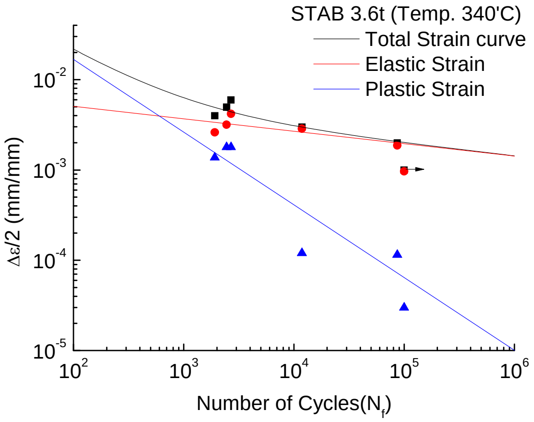
Fig. 6(a) shows low cycle fatigue results of STAB steel treated at 340°C which was the conventional reference. The relationship between total strain and fatigue life is represented whose values are the sums of elastic and plastic strains. Plastic deformation predominates in the strain amplitude range of $\Delta\varepsilon/2=\pm0.4\sim0.6\%$, while elastic deformation predominates in the range of $\Delta\varepsilon/2=\pm0.1\sim0.3\%$. In particular, at the amplitude of $\Delta\varepsilon/2=\pm0.1\%$, there was no material failure during 10^5 cycles.

Fig. 6(b) shows the results of HPF steel treated at 100°C. It can be seen that the plastic deformation is negligible in the range of Δε/2=±0.1~0.7%, which means that the HPF steel is a highly brittle material. The dotted line represents the ε/N curve of STAB steel of reference. Comparing the two ε/N curves, it is observed that STAB steel has higher fatigue strengths in the long and short life regions. The HPF steel treated at 100°C is sensitive to minor defects in its surface and inside due to its low elongation as well as its being brittle as shown in Fig. 4(b).

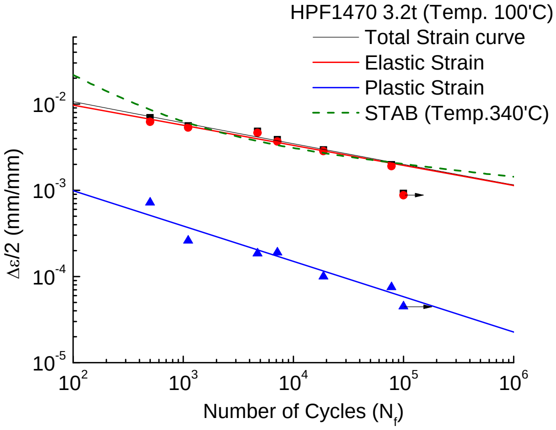
Fig. 6(c) shows the ε/N curve of HPF steel treated at 250°C. It can be seen that elastic behavior is dominant in the strain amplitude range Δε/2=±0.2~0.4%, while plastic behavior is dominant in the range of Δε/2=±0.5~0.8%. In the latter, short life region, it is observed that the HPF steels tempered at 250°C have higher fatigue properties due to its increased elongation, which is not observed in the case of the HPF steels tempered at 100°C. As compared with the ε/N curve of STAB steel of reference, HPF steel has higher fatigue properties both in the short and long life regions.

Fig. 6(d) shows the ε/N curve of HPF steel treated at 340°C. HPF steel has higher fatigue properties than STAB steel in the range of Δε/2=±0.5~0.8% in which plastic deformation is dominant. But in ranges in which elastic deformation is dominant, there is no significant difference in fatigue strength between HPF and STAB steels.

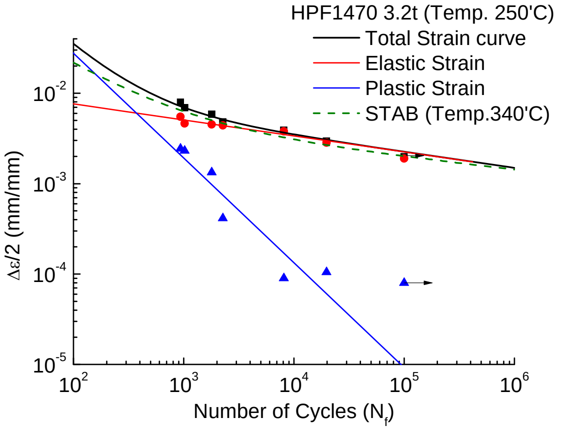
To summarize, fatigue properties of the high strength steel tempered at different temperature are improved in order from HPF tempered at 250°C to HPF tempered at 340°C to STAB and HPF tempered at 100°C.



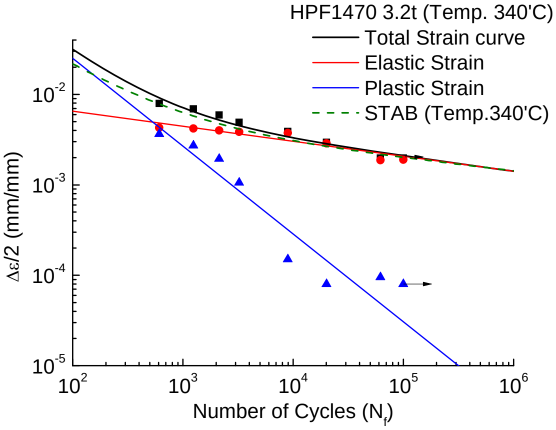
(a) strain amplitude vs. number of cycles curve of
STAB steel tempered at 340°C



(b) strain amplitude vs. number of cycles curve of
HPF steel tempered at 100°C



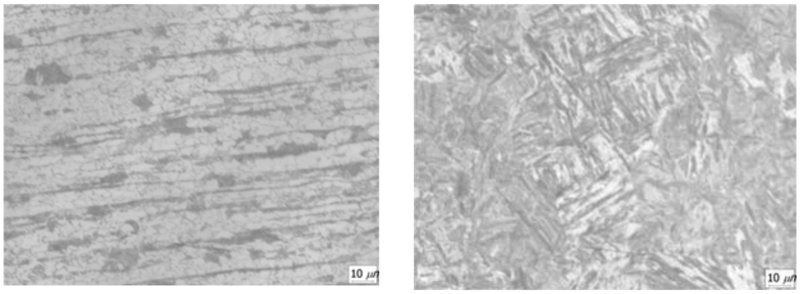
(c) strain amplitude vs. number of cycles curve of HPF steel tempered at 250°C



(d) strain amplitude vs. number of cycles curve of HPF steel tempered at 340°C

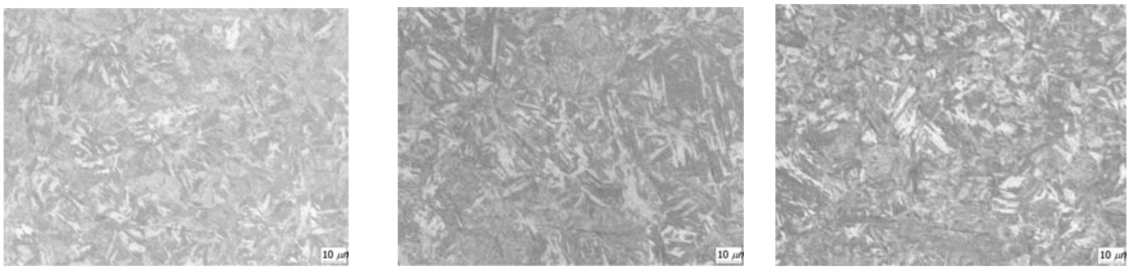
Fig. 6 strain amplitude vs. number of cycles curves

The microstructures of HPF steel before and after quenching were shown in Fig. 7. The tempering effects were gradually obtained tempered at 100°C, 250°C and 340°C were shown with in Fig. 8. The lath tempered martensite was formed with above all tempering temperatures because the HPF steel have the medium carbon content while martensitic microsturctures are complex, consisting of retained austenite, carbide distribution and morphologies [13-14]. The cementites or various kinds of carbides act as obstacles to dislocation silp which is the beneficial effect to the fatigue properties, as well as along lath boundary but the excessive cementite coarsening or a large amount of precipitation, tempered at 340°C reduces the fatigue performance because the presence of grain boundary cementite can reduce the cohesive strength of the interfaces and softens the matrix in the microstructure [15].



(a) (b)

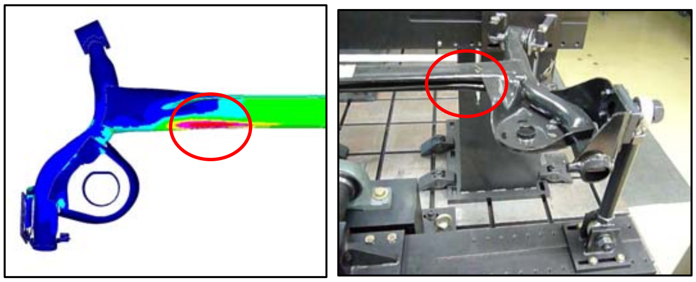
Fig. 7 Microstructure of HPF steel before(a) and after(b) quenching



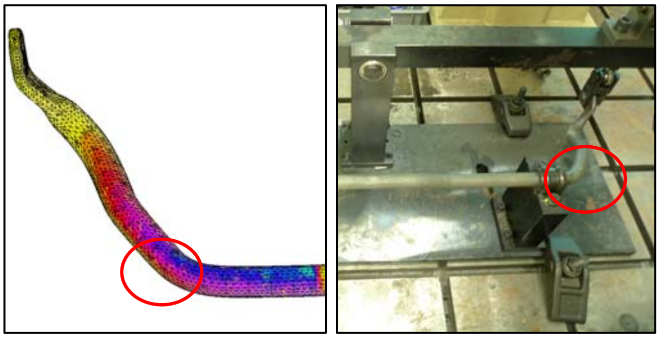
(a) (b) (c)

Fig. 8 Microstructure of HPF steel tempered at 100(a), 250(b), 340°C(c)

For the application of HPF steel, the coupled torsion beam axle and stabilizer which used suspension components in the car developed with the quenching and tempering process. Suspension system, a part closely related with the car vibration and noise, gets repeated loads while driving. So reducing the ground impacts, securing the steering stability, and designing for the structure stability and durability are all important factors in designing vehicles of low vibration/noise. In the design stage, the topology, stiffness analysis, modal analyses were adopted for geometry optimization. For the verification of chassis component performance, the durability test and analysis were performed using the evaluated low cycle fatigue curve. Fig. 9 shows the overview of durability simulation and tests and the circle marks represented the critical points. The examples of the fractograpy with satbilizer were shown Fig. 10, the more torturous and tough crack propagation trace near the defects from the manufacturing process tempered at 250°C was discovered relative to the other cracks with the local plastic deformation which can be absorbed the strain energy related to the strength and ductility, but it does not provide a basis for approaching complex and basically probabilistic fatigue problems. Anyway, the cases of tempered about 250°C were satisfied with the design target life.



(a) Development of coupled torsion beam axle



(b) Development of stabilizer bar with hollow section

Fig. 9 Overview of durability test and analysis

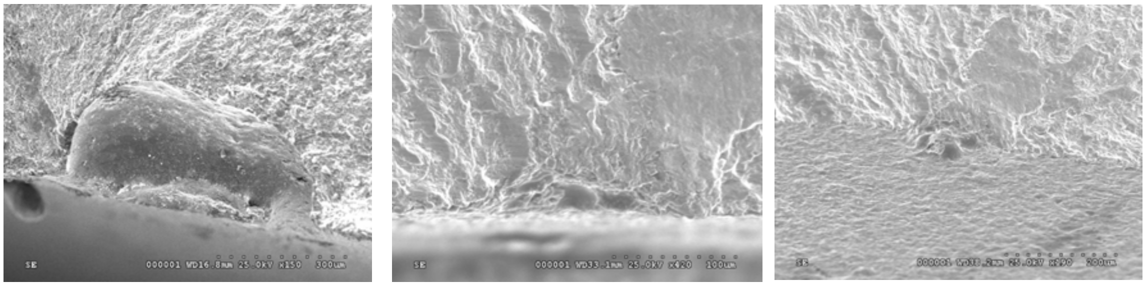


Fig. 10 Fractograpy of HPF steel tempered at 100(a), 250(b), 340°C(c)

Conclusion

In this study, the mechanical and fatigue properties of HPF steel produced with the quenching process have been precisely evaluated in relation to the tempering temperature variation. The following conclusions can be made.

1. As tempering temperature increases, the tensile strength and Vickers hardness decrease while the total elongation increases. But the increasing rate of elongation in the tempering range 250~340°C is higher than the ones in any other tempering ranges, though the tensile strength decreases similarly and TME temperature was about 340°C.
2. The HPF steel tempered at 250°C shows the best result in the low cycle fatigue test, outperforming HPF tempered at 340°C which outperforms STAB and HPF tempered at 100°C.
3. The lath martensite and cementite were discovered in the HPF steel tempered at 250°C which had torturous crack propagation with a local plastic deformation. For the verification of tempering temperature effects, the torsion beam axle and stabilizer were developed. In the durability test, fatigue test of HPF steel tempered at 250°C was satisfied with the design target life.

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