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Development of Ultrahigh-Strength Complex Phase Steel With Enhanced Ductility

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INTRODUCTION

In recent years, ultra high strength steels are used more and more in automotive industry in order to reduce the weight of body in white, such as dual phase steel (DP), complex phase steel (CP), and dual phase steel with improved formability steel (DH)[1-3]. In these kinds of steels, DP steel and DH steel have higher tensile strength and good formability in most cases. But for some components, bending and flanging are needed during cold forming process. However DP and DH steels have a poor stretch flangabiliy, which will not meet the requirements of the OEMs. For CP steel, due to its complex microstructure with bainite, martensite and ferrite, it has a higher stretch flangabiliy but with poor formability compared with DP and DH steels.

In order to get a better bendability and hole expansion ratio, micro alloy elements were added into the steels, such as Nb and Ti. Some studies have shown that adding Ti or Nb could strengthen the ferrite through precipitating[4, 5]. It was revealed that if the difference in hardness between ferrite and martensite can be reduced, the improvement of formability or hole expansion property of DP steel can be achieved[6]. But for these materials, the improvement of hole expansion ratio is not enough, especially for the components with a higher flanging height. Besides stretch flangabiliy, the formability is another problem, in recent years, a newly developed quenching and partitioning (Q&P) process can introduce certain amount of retained austenite in hard martensitic matrix, which can make the steel has a longer elongation[7, 8]. Q&P process can also make the the newly developed ultra-high strength CP steel with improved formability (CH) contain retained austenite embedded in bainitic ferrite and martensite matrix, which can make the CH steel has a higher elongation than traditional CP steel, and CH steel has attracted OEMs' attention[9].

In this research, ultra-high strength CH steel with a minimum tensile strength of 980MPa are studied. Different overaging parameters are adopted to adjust the content of the retained austenite and mechanical properties of the steels, and hole expansion test and 3-point bending test are also conducted to evaluate the flangabiliy and bendability of the annealed steels. After the lab simulation, the suitable annealing parameter is adopted for the industrial production of the steel. We also compared the energy absorption properties of industrial produced CH steel with DP steel using charpy impact test.

DISCUSSION

Experimental procedure

The chemical composition of CH steel used in this study is listed in Table 1, in order to get a high hole expansion ratio, some alloy elements, such as Nb and Ti was also added in the steel. The steel were fabricated using a 50 kg vacuum induction furnace and then cast into square ingot with a dimension of 120mm×120mm×300mm. Before hot rolling, the ingot was homogenized at 1250℃ for 1 h and then hot rolled to a 3 mm thickness sheet. The finish rolling temperature and simulating coiling temperature were 870℃ and 620℃, respectively. The hot rolled plate was then air cooled to ambient temperature. After hot rolling, the plate was pickled using a 25 vol% HCl solution and then cold rolled to 1.5 mm in thickness using a two roll mill. The Ac1, Ac3 and Ms temperatures were calculated using Thermo-Calc Software, and the results are also given in Table 1.

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

Steel	C	Si+Al	Mn	Nb+Ti	Cr+Mo	Ac1	Ac3	Ms
CH	0.19	1.3	2.3	0.04	0.6	717	854	352

The annealing process was adopted using a multi-purpose simulator (VASTRON) in laboratory, the heating cycles was shown in Figure 1, and the detailed annealing parameters are listed in Table 2. In this test, the influence of overaging temperature and time was mainly studied. Because the overaging section of the annealing line can't be too long, so the overaging time is limited.

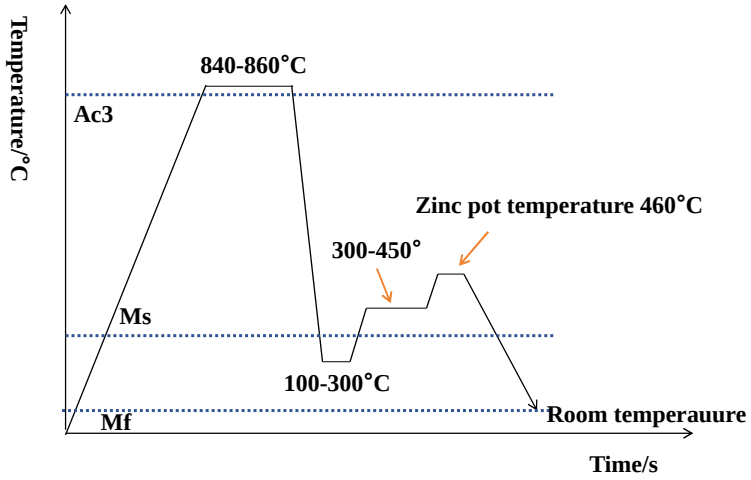


Figure 1 Scheme of the used annealing cycles: continuous galvanizing line (CGL).

Table 2 Different annealing parameters of the steel

overaging temperature, ℃	overaging time, s
320	120
360	120
360	360
420	120

The microstructure evolution of the steels were investigated using scanning electron microscope (SEM, ZEISS EVO-18) and transmission electron microscopy (TEM, JOEL JEM-2100F) both quipped with Oxford energy dispersive X-ray spectrometer (EDS). Thin foils for TEM analysis were prepared by mechanical grinding and twin-jet electropolishing using a solution of 8% perchloric acid and 92% alcohol at -40℃.

Before tensile test, specimens with a gauge width of 25 mm and a gauge length of 50 mm were machined from the annealed steel sheets, and tensile direction were parallel to the rolling direction. Hole expansion test (HET) was carried out using a sheet metal forming machine (Zwick, BUP600) according to the standard of ISO 16630-2017 [10]. Holes with a diameter of 10 mm are expanded until visible cracks occur at the edge of the punched holes. Three-point bending tests were performed on the galvanized CH steel to evaluate the bendability according to VDA 238-100 [11], and the test was performed using a tensile tester (Instron5985) under displacement control at a rate of 0.2 mm/min.

Microstructure evolution

In order to get the influence of overaging parameters on mechanical properties of CH steel, we first investigate the microstructure under various conditions. Figure 2 shows the SEM microstructure of CH steel overaged under different parameters. As can be seen, when the overaging temperature is below 360℃, the microstructure of the CH steel is quite complex, which contains bainitic ferrite, tempered martensite, fresh martensite, ferrite and some retained austenite as shown in figure 2(a), (b) and (d), but with increasing overaging temperature, the content of tempered martensite decrease and the content of

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fresh martensite increase a lot as shown in figure 2(c). When increasing the overaging time, more and more bainitic ferrite and tempered martensite could be found as shown in figure 2(d).

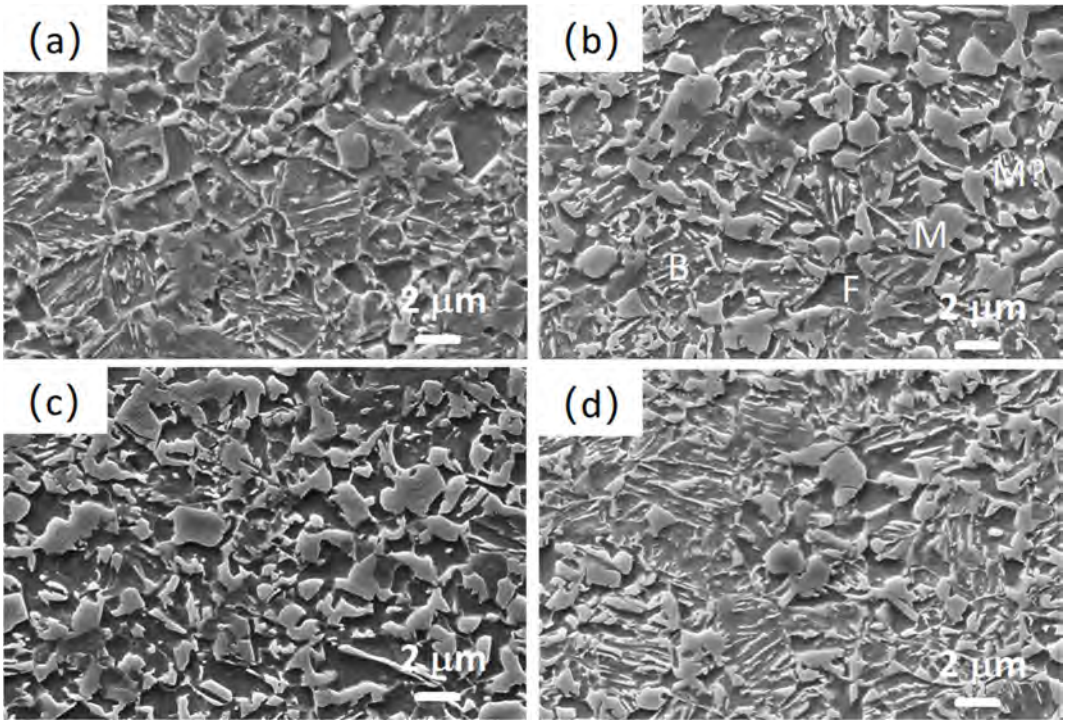


Figure 2 SEM microstructures of CH steel annealed under different parameters: (a)320℃ for 120s, (b)360℃ for 120s, (c)420℃ for 120s, and (d)360℃ for 360s.

In CH steel, retained austenite (RA) was introduced into the microstructure, which can lead to transformation introduced plasticity (TRIP) in the material when deformation happens, so the samples were analyzed using EBSD to determine the volume fraction of RA in CH steel after overaging treatment. Figure 3 shows the EBSD analysis of CH steel under different overaging treatment. When the overaging temperature is 420℃, which is higher than Ms temperature, the content of RA is about 6%, and it is blockly like morphology as shown in Figure 3(a). Decreasing the overaging temperature can lead to more RA like Q&P process, and change the morphology of martensite as shown in Figure 3(b), and for the longer holding time, more austenite fraction can be introduced as shown in Figure 3(c).

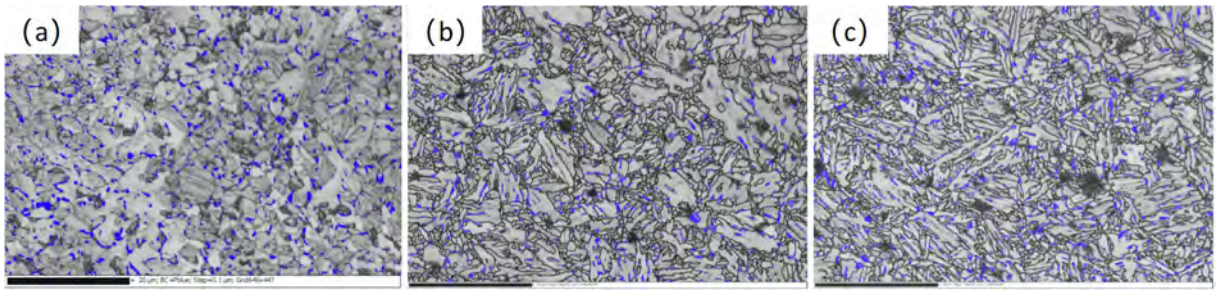


Figure 3 EBSD results of the steel (a) overaging at 420℃ for 120s, (b) overaging at 360℃ for 120s and (c) overaging at 360℃ for 300s

In order to understand the morphology at the microscopic scale, TEM was carried to study retained austenite. Different size and morphology of retained austenite could be found in the microstructure. The first one is the blocky like retained austenite, which are distributed in ferrite matrix as shown in Figure 4(a). Another one is film like retained austenite, and the width of the

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film is about 100-200nm as shown in Figure 4(b). Actually, retained austenite is introduced to enhance the formability of the steel, but in some cases, local formability is also very important, such as the ability to flangabiliy and bendability. The TRIP effect during stamping could suppress the formation of microcrack and can also delay the microcrack propagation when microcracks formed at large strain under the condition of not too much retained austenite[12]. For CH steel in this study, micro-alloy Nb and Ti were added to enhance ferrite, so precipitation could be found in steel as shown in Figure 4(c), and the chemical composition of the precipitation contains Nb and Ti as EDS analysis shown in Figure 4(d), so it is supposed to be the (Nb, Ti)C, and the size of precipitation is about 2-10 nanometre.

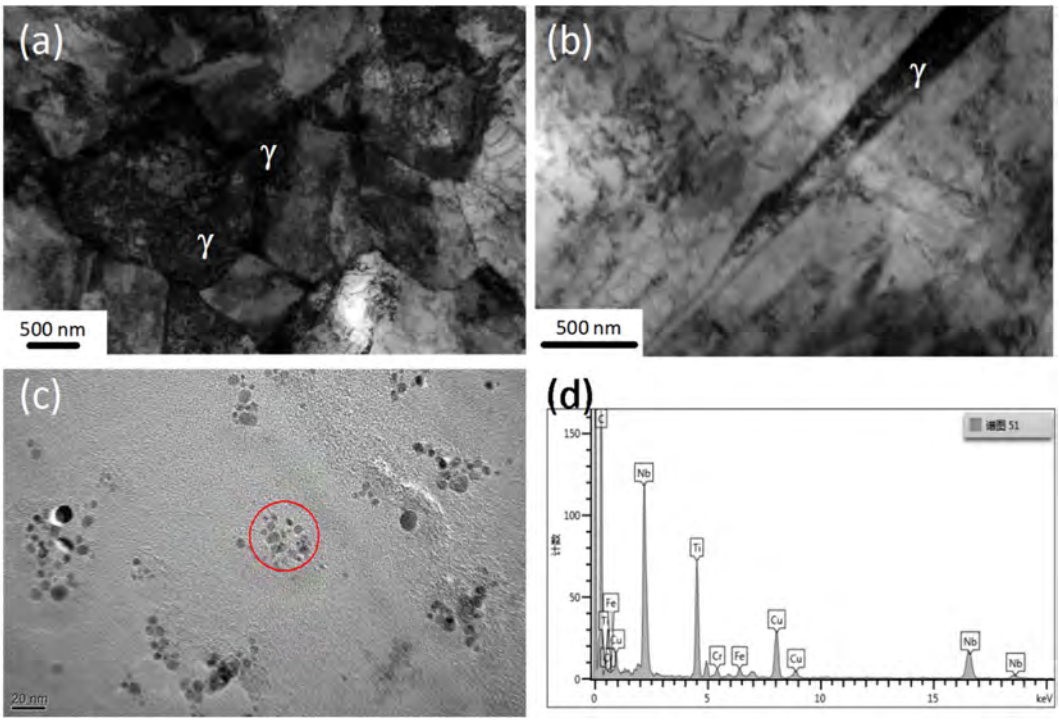


Figure 4 TEM microstructure and precipitation of CH steel: (a) overaging at 420℃ for 120s, (b) overaging at 360℃ for 120s, (c) precipitation in CH steel overaged at 360℃ for 120, and (d) EDS analysis of precipitation.

Mechanical properties

Tensile tests were carried out for CH steel under different overaging treatments, and for comparison we also conducted tensile test on a traditional CP980 steel. The engineering stress-strain curves of CH980 and CP980 are shown in Figure 5, and average values of yield stress (YS), ultimate tensile stress (UTS), uniform elongation (UE), and total elongation (TEL) are given in Table 3. It can be seen the steel in this research has a very high ultimate tensile strength of about 1000MPa. When the steel was overaged at 420℃, the tensile strength is nearly 1200MPa, but the elongation is only 9%. When overaging temperature is 360℃ and 320℃, the UTS of the steel is about 1000MPa, and under the effect of retained austenite, the TEL is about 15%, and the UE is around 10%, which means the steel has a good formability.

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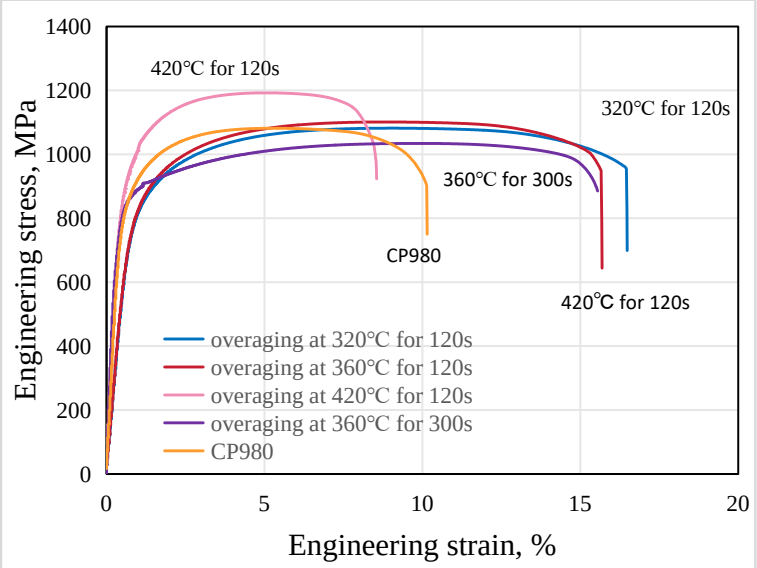


Figure 5 Engineering strain-stress curves at different overaging temperatures for the investigated steel.

Table 3 Mechanical properties of samples after different overaging treatment.

Ref.	YS(MPa)	UTS(MPa)	UE(%)	TEL(%)	Yield ratio
320℃ for 120s	835	1011	8	15	0.82
360℃ for 120s	849	1069	9	16	0.79
360℃ for 300s	791	1031	9	15	0.77
420℃ for 120s	922	1191	4.5	9	0.77
CP980	824	1085	4.5	9.5	0.76

Hole expansion ratio and bendability

Hole expansion ratio is an effective index to evaluate the stretch-flangabiliy of the steel. Furthermore, if the hole was punched, the hole expansion test can also reflects the edge crack sensitive to micro-damage of the material during the stamping process. Steels overaged under different parameters were tested and the results are shown in Table 4. As can be seen, the hole expansion ratio of CH steel increase firstly with increasing overaging temperature, then decrease when overaging temperature reach 420℃. The maximum hole expansion ration is 53%, which is much higher compared with traditional complex phase steel CP980.

Table 4 Hole expansion ratio of CH980 annealed under different overaging temperatures.

Ref.	Hole expansion ratio, %
320℃ for 120s	42
360℃ for 120s	53
360℃ for 300s	47
420℃ for 120s	26
CP980	35

Beside hole expansion test, three-point bending test was also performed to determine the bending angle to get information about the formation behaviour and the sensitivity of the steel in this study to failure during forming processes with dominant bending components or at crash load. For comparison, we also chose CP980 to compared the bending angle. Figure 6 shows

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the schematics of three-point bending test and the measurement of the bending angle. The bending angles of steel in this study and CP980 after bending test were shown in Table 5. The bending properties are quite similar with hole expansion ratio, with increasing overaging temperature, the bending angle of CH steel increase, but when the overaging temperature is 420℃, the bending angle decrease. Considering CP980, the bending angle is always smaller than CH980, furthermore, CH980 and CP980 exhibit different springback. The average springback angle of CH980 is 13.7° after unloading, but for CP980 it is only 7.1°. The springback is related to the yield ratio, so the springback is more serious for CH980 with higher yield ratio. When CH980 is used for new component, the constitutive model of CH980 should be considered firstly.

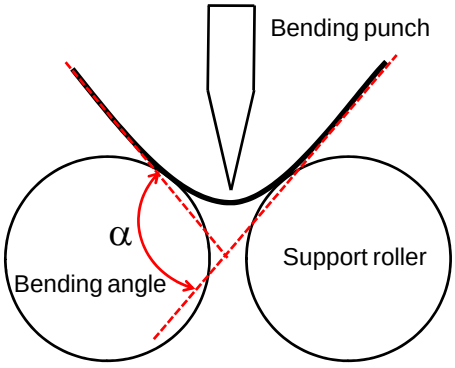


Figure 6 Schematics of three-point bending test

Table 5 Comparison of bending angle of CH980 and CP980

Steel	Ref.	Bending angle, °	Bending angle after springback, °
CH980	320℃ for 120s	96.4	110
	360℃ for 120s	98.1	113.9
	360℃ for 300s	96.3	108.8
	420℃ for 120s	93.1	106
CP980	CP980	90.3	97.4

In order to verify that this CH steel has a better energy absorption capacity in component applications, we used the Charpy impact test to verify the impact energy of this material, and in order to compare with the conventional material, we also selected the traditional CP980 as the comparison material. Since the steel sheet we used was only 1.5 mm in thickness, it is hard for impact test. In order to ensure that the test could be carried out, we laminated the steel sheets to be 10 mm, and the laminated impact specimen was formed. The test was carried out as shown in Figure 7. It can be seen that CH980 always has a much higher impact energy compared with traditional CP980, which means that if CH980 was used as the structural components in body in white, it can absorb more energy in the event of a collision, so that the passengers can be better protected.

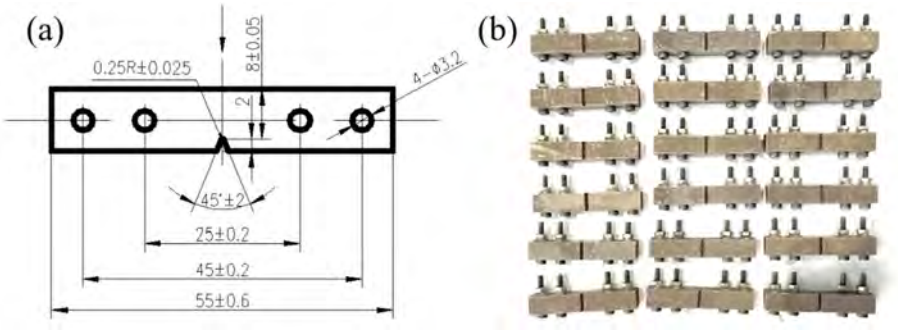


Figure 7 Schematics of dimension of the specimen for the charpy test and the samples used in this study.

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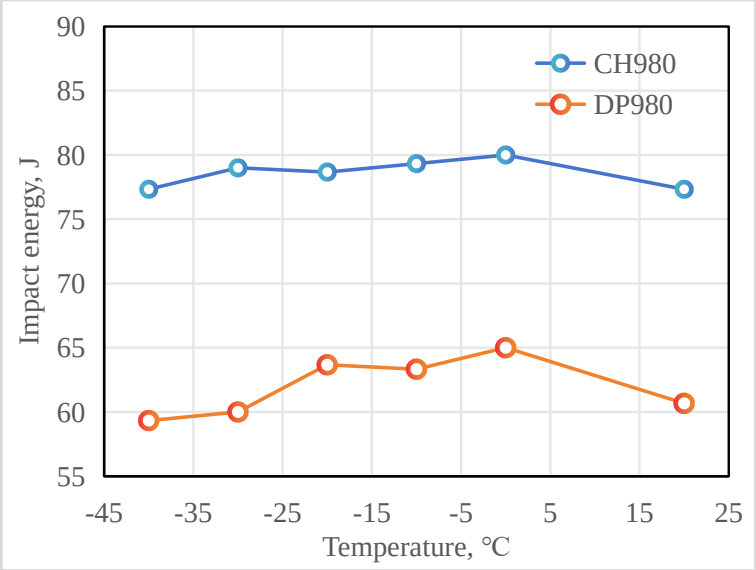


Figure 8 Relationship between temperature and impact energy of CH980 compared with traditional CP980 steel.

It is known that the battery-pack systems are very sensitive to loads and crashworthiness, which can lead to an electric short circuit, cell venting, and rapid dissipation of energy[13]. Because batteries are not allowed to be damaged, so the profile is considered to be with higher strength and energy absorption capacity to protect the battery[14]. Here we recommended a battery box using CH980 as a roll-formed crash profile as shown in Figure 9.

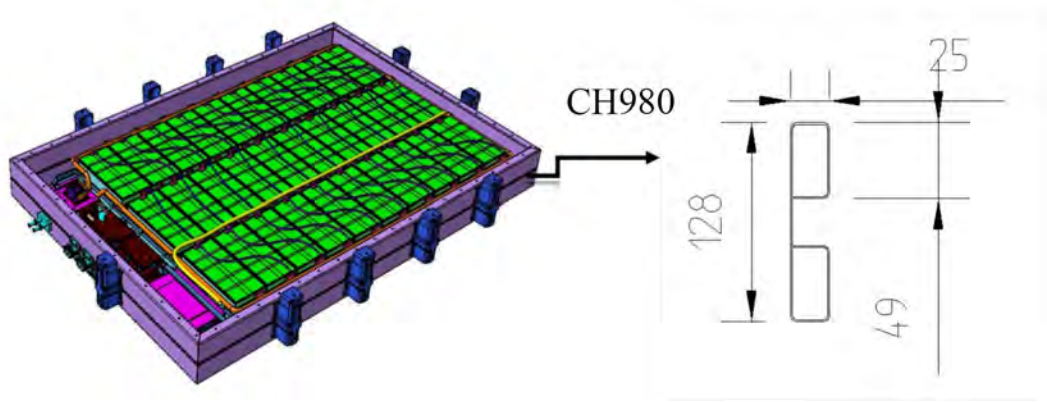


Figure 9 Roll-formed crash profile in a battery box

CONCLUSIONS

A complex phase steel with enhanced ductility was studied in this research, and the results are summarized as follows.

1) Overaging temperature influenced ultimate tensile strength and yield strength of CH steel a lot. Most of the retained austenite are film like morphology when the steel was overaged at temperature lower than 360℃, and blocky retained austenite can be found when overaging temperature is at 400℃.
2) When overaging temperatures is between 340℃ and 360℃, CH steel has a total elongations of about 15%, which is much higher than CP980, meanwhile the hole expansion is from 42% to 46%, which is also higher than CP980.
3) The bending angle is above 93.1° for CH steel, and CP980 is only 90.3°. CH steel has a better bendability of about compared with CP980, but with a more serious springback.
4) The CH steel in this study has a much better energy absorption ability compared with traditional CP980 steel, which enables it can be used for some energy absorption components in crash profile in a battery box.

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