

Development of 590 and 780MPa Grade High-ductility Steel Sheets

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ABSTRACT

A high-ductility TRIP steel sheet has been developed to achieve weight savings in automotive bodies. When TRIP steel is deformed by stamping, etc., the transformation of the retained austenite distributed in its matrix structure into martensite controls the strain concentration. This gives the material higher formability than the conventional steels. However, TRIP steel sheets contain a higher amount of Si than the conventional steel sheets, and this can cause the coating quality of the material during hot-dip galvannealing and the ability of cold rolled sheets to accept coatings to decline. A TRIP steel displaying the required strength and formability while possessing identical coating quality and e-coating performance to conventional steels has therefore been developed by optimizing the amount of C, Si and Mn, the main constituent elements of the steel, adding an element which controls Si concentration to sheets for hot-dip galvannealed (GA steel sheet) and removing the concentrated Si surface layer of non-galvannealed sheets for cold rolling (CR steel sheet). As a result, it has been possible to achieve an identical level of formability in 590 MPa and 780 MPa class steel sheets when compared to 440 MPa and 590 MPa class conventional high strength steel sheets (HSS) respectively. In addition, the new steel possesses identical energy absorption characteristics to the conventional HSS but is 10% lighter, enabling weight per vehicle to be reduced by more than 10 kg when the new sheets are applied.

1. Introduction

Auto manufacturers are increasingly tending to use high strength steel sheets (HSS), in particular steels of tensile strengths of 590 MPa and above, in body framework parts in order to achieve weight reductions while complying with requirements for improved collision safety performance. These requirements continue to grow more stringent every year⁽¹⁾. To maximize the weight reduction benefits of HSS, they must be applied to as many parts as possible. However,

formability declines as tensile strength increases, and this places limits on the specific parts for which HSS can be used.

In our attempt to achieve significant weight reductions, the authors focused on TRIP steel, which possesses a higher level of strength and formability than the conventional steels while continuing to meet the coating and spot welding performance requirements for automotive materials.

This paper discusses the characteristics of the newly developed steels in comparison to the conventional steels, with a focus on coating quality, e-coating performance, formability and energy absorption properties.

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2. Development Goals

In terms of the relationship between strength and formability in steel sheets, tensile strength and elongation are normally in the relationship shown in Fig. 1. Higher elongation means superior formability: in the graph, the higher a sheet registers in the upper right, the better its characteristics.

At the time this development project was commenced, the 2001 model year CIVIC applied the greatest proportion of HSS in the framework. HSS, mainly solid solution strengthened 440 MPa class and precipitation hardened 590 MPa class, represented 57% of the weight of the framework⁽²⁾. The development project established the goal of replacing the 440 MPa and 590 MPa HSS with steels of a strength one rank higher, 590 MPa and 780 MPa HSS respectively. The goal was to improve the mechanical properties of the steels in order to achieve an equivalent level of formability in a 590 MPa HSS to a 440 MPa HSS, and in a 780 MPa HSS to a 590 MPa HSS.

The project investigated the use of 980 MPa HSS, but the achievement of this level of tensile strength in a TRIP steel increases the amount of carbon required in the composition to more than 0.30 mass%, generating difficulties with spot welding, among other issues, which would potentially limit the range of parts for which the steel could be used. Other than TRIP steels, cold rolled dual phase 980 MPa HSS is already in use and can also be considered, but it does not possess sufficient formability, once again placing restrictions on its use. It was therefore judged that the maximum weight reduction benefits would be achieved by establishing the targets for tensile strength at 590 MPa and 780 MPa.

Yield strength was another mechanical property of the steel which was considered. Having determined the parameters for weight reduction benefits, studies were conducted to ensure that the new steel would possess equivalent collapse strength to the conventional solid solution strengthened 440 MPa and precipitation hardened 590 MPa steels. The properties shown in Table 1 were established as targets on the basis of these studies.

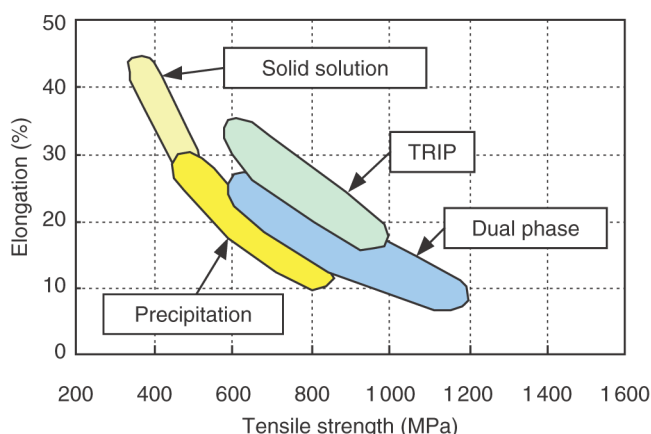


Fig. 1 TS-EL balance of high-strength steel

In addition to the mechanical properties discussed above, GA steel sheets for automotive use require good coating performance and GA and CR sheets require good e-coating and spot welding performance. The development goal

established here was to achieve performance in these areas equivalent to that displayed by conventional HSS sheets.

Table 1 Target for mechanical properties of TRIP steel

Grade	YS(MPa)	TS(MPa)	El(%)
GA 590TRIP	360 min.	590 min	32 aim
GA 780TRIP	400 min.	780 min.	25 aim
CR 780TRIP	400 min.	780 min.	27 aim

3. Specifications of Steels

3.1. Principle of the TRIP Effect

This section will provide a basic introduction to the properties of TRIP steels which were considered in determining the specifications of the new steels. TRIP is an abbreviation of transformation induced plasticity. This phenomenon originates in the construction of the microstructure. An example of this microstructure is shown in Fig. 2. As the photograph shows, the microstructure is characterized by the dispersion of metastable retained austenite in volume fractions from a few % up to around 15% in the matrix structure, which is composed of ferrite, etc. When the retained austenite receives a deforming strain, as for instance when the material is pressed, it is transformed into martensite. The martensite is in a hard phase, and the sections which have undergone transformation are therefore relatively stronger than the sections which have not. As a result, the deforming strain is transmitted to the relatively weaker, untransformed sections. The repetition of this phenomenon prevents the strain from concentrating in one area, which could be the point of origin of breakage, thus increasing the ductility of the material. Ensuring that the steel contains this metastable retained austenite is therefore the major consideration in the manufacture of TRIP steels.

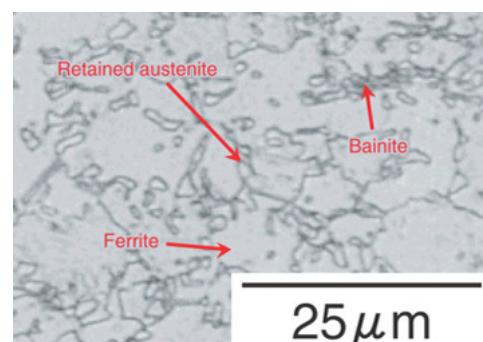


Fig. 2 Microstructure of TRIP steel

3.2. Study of Basic Components of Steels

Like other steel sheets, the required properties of TRIP steels are generally achieved through appropriate composition of the material and the application of heat treatments. Figure 3 shows an outline of the heat treatment used for TRIP steels. Almost all steel sheets contain carbon, and in the case of TRIP steels it is desirable to concentrate this carbon as much as possible in austenite, in order to ensure that metastable retained austenite is obtained⁽³⁾. The most important factors in achieving this are the cooling and overaging processes. During cooling a ferrite phase precipitates from the austenite. Because the solubility of carbon in ferrite is low, as ferrite precipitates carbon concentrates in the austenite. As the steel is aged at

temperatures of 400-500 °C, carbon is further concentrated in the process of bainitic transformation. As a result the austenite, which is stable at high temperatures, remains in a semi-stable state up to room temperature. The most important component of the steel in this process is Si. Si is one of the elements making up ferrite, and does not exist in solid solution in cementite, and it therefore retards pearlite transformation during the cooling process, thus promoting the concentration of carbon which occurs with its precipitation from ferrite⁽⁴⁾. This provides a base for the further concentration of carbon in the overaging process which the steel undergoes after cooling. In addition, the fact that Si exists in solid solution in ferrite contributes to strength. Al is known to function in the same way as Si⁽⁴⁾. Mn is another important element in TRIP steels. Mn is one of the elements which makes up austenite, and therefore contributes to the formation of the retained austenite in the steel, and also contributes to strength by being present in the ferrite in solid solution. Therefore, in addition to carbon, the most basic component of all steel sheets, the important components of TRIP steels are Si or Al, which contribute to the formation of retained austenite and increase strength by being present in ferrite in a solid solution, and Mn, which is a component which makes up austenite and enables the strength of the material to be regulated. In this research project, a basic composition of C-Si-Mn system was selected as providing an excellent balance between strength and ductility.

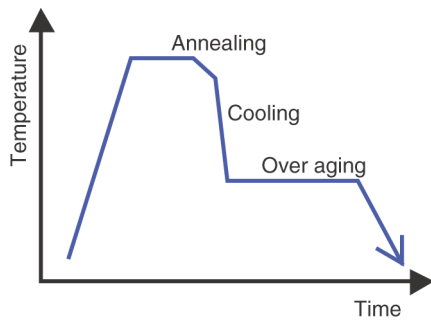


Fig. 3 Heat treatment diagram

3.3. GA TRIP Steel

After selection of C-Si-Mn system as the basic composition of the new steel, the specifications of the steel and the production process were optimized to balance excellent coating performance on GA sheets with the achievement of the required mechanical properties.

3.3.1. Causes of decline in coating performance

Si plays an important part in the achievement of the required properties in TRIP steel, but it also has a negative effect on coating performance in the hot dip galvanizing process. This is because in the annealing process during production, Si concentrates on the surface layer of the steel sheet as compound oxides with Mn^{(5),(6)}. The continuous galvanizing line (CGL) used in the production of GA sheets generally includes the processes shown in Fig. 4. Of these, the major purpose of the annealing process is to achieve the desired mechanical properties in the TRIP steel, but at the same time it is also used to adjust the surface condition of the steel to ensure successful hot dip galvanizing. In the annealing process, the steel sheets are first heated in a non-oxidizing furnace, which burns off residues of the rolling oil used in cold rolling remaining on the surface at the same time

as forming a thin iron oxide layer. The sheets are then placed in a mixed nitrogen-hydrogen reducing atmosphere to remove the oxide layer and activate the surface. These treatments enable a good coating to be achieved in galvanizing, the next process. However, Si and Mn form oxides more easily than Fe does, and oxidation can therefore proceed even in an atmosphere which is reducing for steel. The concentration of Si and Mn on the surface as compound oxides causes wettability and adhesion between the galvanizing solution and the steel sheet to decline, and can lead to defects in the coating, including tiny areas in which the coating has failed.

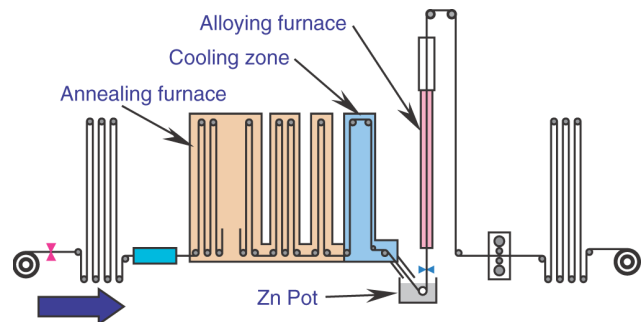


Fig. 4 CGL process flow

3.3.2. Coating quality and mechanical properties

Another issue in the manufacture of GA TRIP steel sheets is the achievement of a balance of coating quality and mechanical properties. After galvanization, GA steel sheets are subjected to an alloying heat treatment, as shown in Fig. 4. In this process the substrate steel and the surface coating of zinc diffuse into each other, forming a steel-zinc alloy, otherwise known as GA steel. In the manufacture of GA TRIP steels, the alloying heat treatment process shown in Fig. 3 doubles as the overaging. Therefore, the fact that the optimum temperatures used in the two treatments differ generates certain issues. Figure 5 shows this in schematic form. The optimum temperature for the alloying heat treatment is 500-550 °C. Below this, alloying is affected and sufficient coating quality for a GA steel cannot be obtained. The optimum temperature for the overaging process is lower at 400-500 °C; if the temperature goes above this range, the retained austenite breaks down and the ductility declines. This means that in order to balance coating quality and

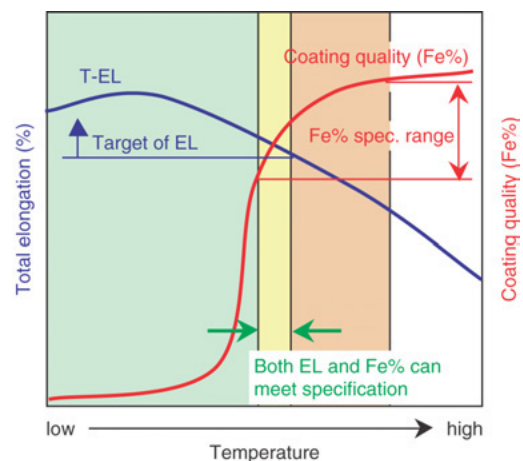


Fig. 5 Relationship between elongation and coating quality

mechanical properties, the range of temperatures which can be used is narrow.

3.3.3. Specifications and method of manufacture of GA TRIP steel

This section will discuss how the issues outlined above were resolved. With respect to the decline in coating quality, optimization of the thickness of the oxidizing layer formed in the non-oxidizing furnace in the annealing process enabled the concentration of Si and Mn on the surface in the following reducing process to be controlled to a certain extent⁽⁶⁾. In addition, elements have been added to the basic composition of C-Si-Mn system to control the concentration of Si and Mn on the surface of the steel sheet. Figure 6 shows a photograph of a cross-section of the coating layer achieved as a result. The coating layer is not inferior to that achieved on the conventional GA steel and no reduction in adhesion can be observed. The measures adopted can therefore be judged successful in controlling the reduction in coating performance caused by Si and Mn. The mechanism of this effect may be considered as follows:

The elements added to the composition were selected on the basis of oxidizing less readily than Fe, and a steel oxide layer therefore forms when the material is heated in the production process or placed in the non-oxidizing furnace during annealing, causing the added elements to concentrate on the surface. This is believed to have the same effect as the formation of a layer on the steel sheet surface which controls the concentration of Si and Mn.

To achieve a balance between coating quality and mechanical properties, the concentration of Al in the zinc bath was controlled to enable the temperature used for the alloying process which follows galvanization to be lowered close to the optimum temperature to ensure the desired mechanical properties.

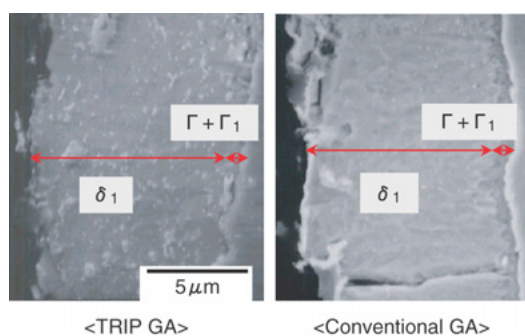


Fig. 6 Comparison of coating layer (TRIP and conventional)

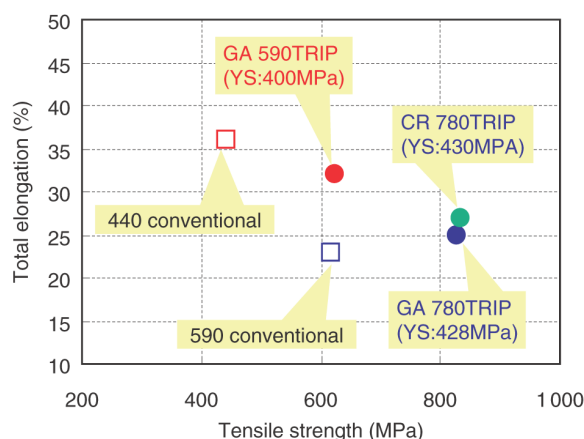


Fig. 7 Comparison of TS-EL balance

The mechanical properties of the steel were tested after the measures described above had been implemented. As Fig. 7 shows, the results of these tests indicated that the steel sheet satisfied requirements for a GA steel sheet, and target values for strength and total elongation have been achieved.

3.4. CR TRIP Steel

With a basic composition of C-Si-Mn system, materials specifications and the production process were optimized to achieve good e-coating performance and the required mechanical performance for CR TRIP steel.

3.4.1. Causes of decline in e-coating performance

In addition to its effect on e-coating performance in GA steels, Si has a negative effect on e-coating performance in CR TRIP steels. As in the case of GA TRIP steels, the mechanism of this effect is the concentration of Si and Mn on the surface during annealing, but it is particularly related to the concentration of Si. Figure 8 shows the distribution of elements on the surface of a CR TRIP steel sheet from the initial stages of development, and a marked concentration of Si can be observed. Figure 9 shows the results of hot salt water dipping tests conducted to determine the quality of the chemical conversion film forming when the sheet undergoes phosphate treatment and the level of adhesion of the e-coat. There are a large number of gaps and irregularities in the chemical conversion film, and the width of peeling in the hot salt water dipping tests was more than two times the standard figure. E-coating performance was therefore judged as inadequate.

3.4.2. Material specifications and production process for CR TRIP steel

In order to improve the e-coat performance of the CR TRIP steel, the project first attempted to modify the conditions of the phosphate treatment to improve etching and increase the mass of the film. However, despite the fact that the chemical conversion film showed a slight improvement in quality, no improvement was observed in the adhesion of the e-coat. The following methods were therefore adopted to remove the concentration of Si on the steel surface:

- (1) Reduction of the amount of Si in the steel: The concentration of Si on the surface of the steel was controlled by reducing the amount of Si in the steel while ensuring that sufficient Si was added to achieve the required mechanical properties.
- (2) Capture of the Si on the surface in an oxide scale layer and removal of the layer by descaling.

Other methods were tested, including strengthening the pickling, using surface grinding, pickling and alkali cleaning after the annealing process. But their effectiveness could not be verified. The addition of elements to control the concentration of Si on the surface of the steel which proved effective in the case of GA steels was ruled out from considerations of increases in materials costs.

Figure 10 shows the results of measurements of the distribution of elements on the surface of the steel after the measures described above were implemented. It is clear that there has been a significant reduction in the concentration of Si compared with the results shown in Fig. 8. The results of tests on the quality of the chemical conversion film and resistance to hot salt water conducted on the steel after the measures were implemented are shown in Fig. 11. No gaps or irregularities can be observed in the film, and peel width is also within standard values. The results of corrosion resistance tests conducted after e-coating also met the standards, and the e-coat can be judged as satisfying automotive performance requirements.

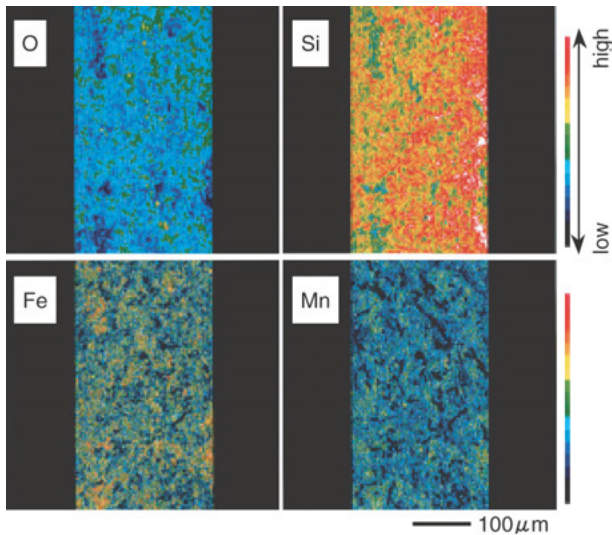


Fig. 8 Surface analysis (EPMA)

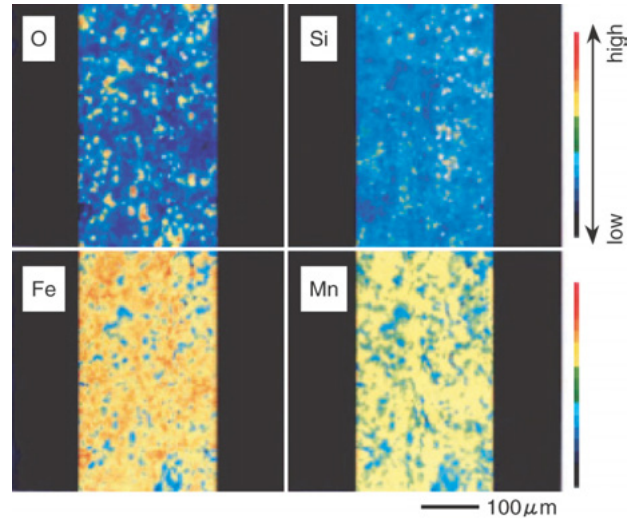


Fig. 10 Surface analysis (EPMA post countermeasure)

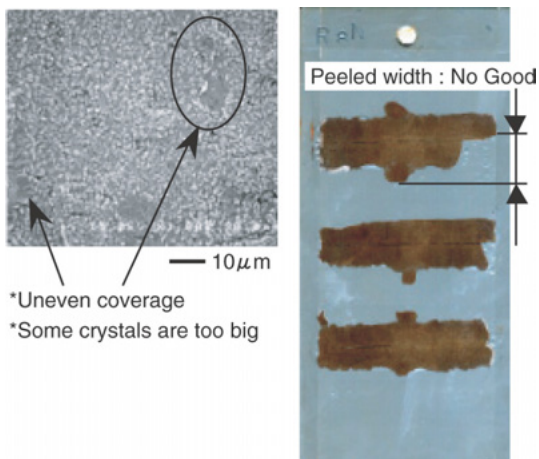


Fig. 9 Phosphatability and E-coat adhesion

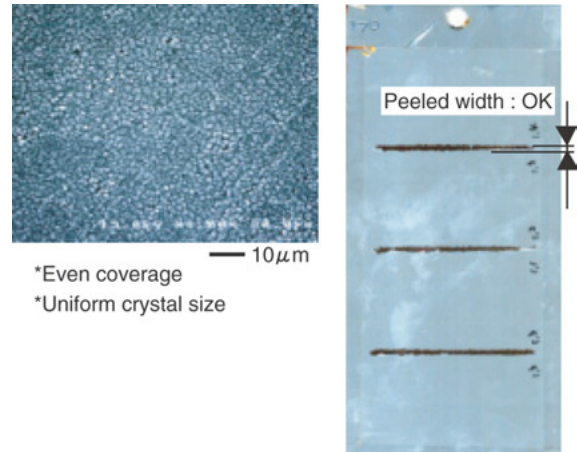


Fig. 11 Phosphatability and E-coat adhesion (post countermeasure)

4. Test Results

Tests were conducted to compare the newly developed TRIP steels to the conventional steels.

4.1. Formability

4.1.1. Limiting dome height tests

Figure 7 shows comparisons of the tensile strength and elongation of the newly developed TRIP steels and the conventional HSS. As the Figure shows, the TRIP steels have a better balance of strength and ductility than the other steels, and this can be interpreted as representing higher formability. However, elongation is not a sufficiently rigorous measure to enable comparison of formability, and limiting dome height tests were therefore conducted. These tests enable comparisons of formability under conditions closer to actual pressing than those of tensile tests. The tests measured the maximum height of deformation and the strain generated when rectangular test pieces were pressed by a punch with a fixed curvature or when bulging was conducted by fluid pressure until breaking, as shown in Fig. 12(a). Varying the dimensions of the short edge of the test piece enabled the



Fig. 12(a) Forming test method

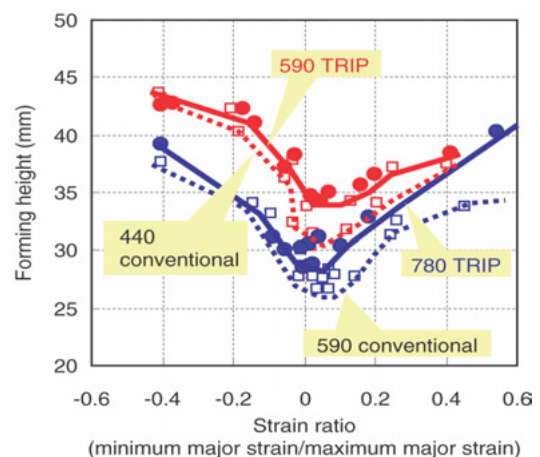


Fig. 12(b) Comparison of formability

ratio between the maximum major strain and the minimum major strain which is generated perpendicular to it to be varied.

The results of these tests are shown in Fig. 12(b). Comparison of the position of each of the steels on the graph indicates that the 590 and 780 MPa class TRIP steels have equivalent or superior formability to the conventional 440 and 590 MPa class HSS. This demonstrates that initial development targets have been achieved, and that the 590 and 780 MPa class steels can be used to replace, respectively, 440 and 590 MPa class steels in automobile body framework parts.

4.1.2. Prototype stamping trials

Trial stampings of prototype shapes were conducted to compare the formability of the steels for actual vehicle parts. As shown in Fig. 13(a), a test piece with a pouched edge was produced, and the height to which it was possible to form the pouched section was compared. Figure 13(b) shows the results. Under conditions closer to those of actual production, the new 590 and 780 MPa class TRIP steels demonstrate equivalent or higher levels of formability to the conventional 440 and 590 MPa class HSS, as they did in the limiting dome height tests.



Fig. 13(a) Appearance of prototype die

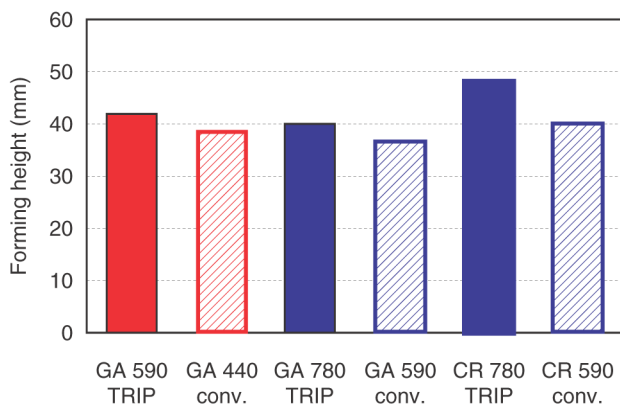


Fig. 13(b) Comparison of formability

4.2. Spot Welding Performance

In addition to formability, another important property for automotive steel sheets is good spot welding performance, and tests were conducted to verify this for the new steels. Tensile shearing tests and cross tension tests were conducted to measure static strength and fatigue strength in order to evaluate spot welding performance. Figure 14 shows the results of static tensile shearing strength tests as an example. When the results are organized in terms of sheet thickness (t), nugget diameter (N.D.) and the tensile strength of the steels (TS), the parameters that determine spot welding strength, it is clear that the spot welding strengths of the TRIP steels are

within the range of distribution for the conventional materials which have been successfully employed in mass production, and strength can be assured with standard control of nugget diameter. The results of other tests of spot welding strength also showed that the performance of the new steels equaled that of the conventional steels.

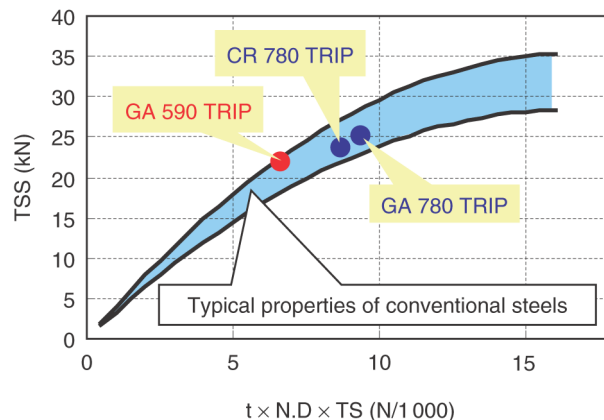


Fig. 14 Strength of spot-welded joint

4.3. Energy Absorption Properties

Given that the main purpose of applying HSS in framework parts is to balance increased collision safety performance with weight reductions, the energy absorption properties of the steels, which relate directly to collision performance, are extremely important factors. Tests of crushing deformation, an important mode of deformation in front and rear collisions, were therefore conducted to compare the energy absorption of the TRIP steels with that of the conventional HSS. Test samples were constructed by bending 1.6 mm thick sheets of 590 and 780 MPa class TRIP steel, 440 MPa solid solution strengthened HSS and 590 MPa precipitation hardened HSS and spot welding them to form hat-shaped quadratic prisms. The samples were subjected to bake-hardening (BH) treatment at 170 °C for 20 mins, after which they were subjected to the test procedures shown in Fig. 15. In the tests, a 160 kg weight was dropped on the test pieces from a height of 12 m, and the energy absorbed until deformations of 50, 100 and 150 mm were produced, was determined. The results of these tests are shown in Fig. 16, and show an increase of approximately 30% in energy absorption in the new 590 MPa and 780 MPa class TRIP steels against the conventional 440 MPa and 590 MPa class

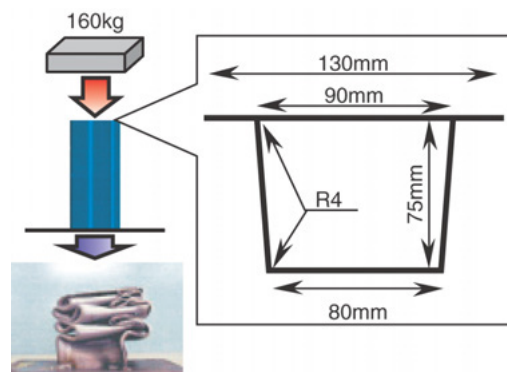


Fig. 15 Test method

HSS respectively.

The weight reduction effect of the TRIP steels was estimated on the basis of these results. The equation below, which shows the relationship between the thickness and shape of the materials on energy absorption in a quadratic prism, was used in the estimates⁽⁷⁾:

$$E_{ab} = C \delta L^{1/3} t^{3/5} \quad (1)$$

E_{ab} : Amount of energy absorbed
 C : Constant
 δ : Amount of deformation
 L : Length of side
 t : Sheet thickness

Equation (1) was used to find the relationship between energy absorption and thickness for steel sheets of identical side length (cross-sectional shape) for a deformation of 100 mm. The results of these calculations are shown in Fig. 17. The calculation results show that the energy absorption of a TRIP steel sheet of 1.4 mm is identical to the energy absorption of a conventional HSS sheet of 1.6 mm. The weight reduction benefit in this case is 12.5%, the difference between the thicknesses of the two sheets. The weight reduction benefit will increase or decrease depending on the thickness of the original sheet to be replaced, but with a range of thicknesses between 1.0 and 2.0 mm, which are the most widely used in automobile bodies, weight reductions of more than 10% can be expected.

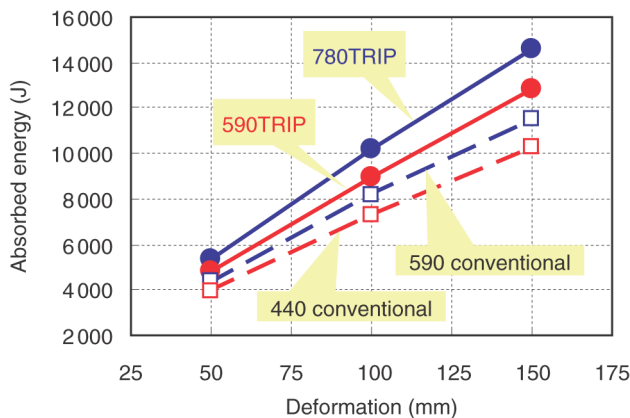


Fig. 16 Comparison of absorbed energy

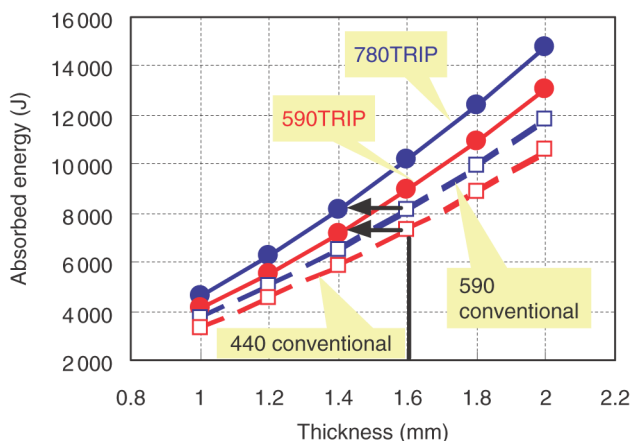


Fig. 17 Estimation of thickness

5. Effect in Vehicle Use

The effect of the new steels in vehicle use was verified using simulations of a rear collision with the TRIP steel sheets applied to the rear framework. The 440 MPa solid solution strengthened steel and the 590 MPa precipitation hardened steel, which currently are the most widely used at Honda, were used for comparison. The results of these simulations are shown in Fig. 18. The thickness of both the 590 MPa and 780 MPa TRIP steels was calculated as 0.2 mm thinner than that of the conventional 440 and 590 MPa class HSS. The results show almost identical deformation in the conventional HSS and the new TRIP steels, indicating that an equivalent level of collision safety performance can be achieved with a weight reduction of approximately 10% in the rear frame.

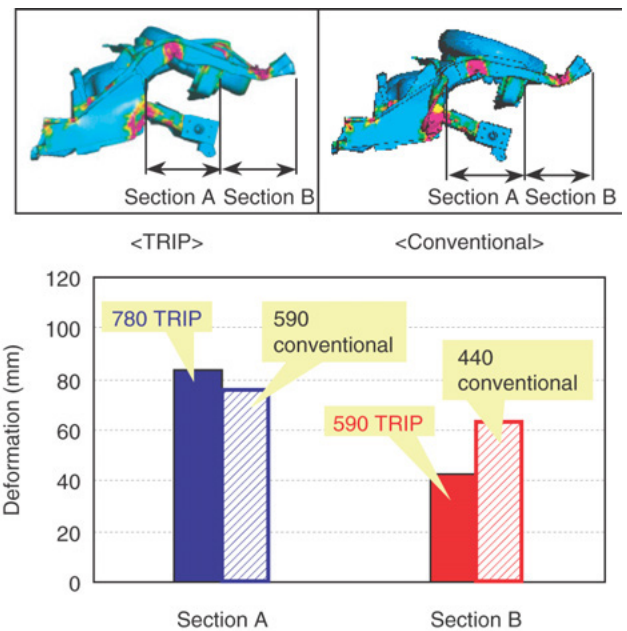


Fig. 18 Comparison of deformation (simulation)

6. Conclusion

590 and 780 MPa class TRIP steels have been developed to enable weight reductions to be achieved in automobile bodies. The results of the development project are as follows:

- (1) Elements which control the concentration of Si were added to the basic composition of C-Si-Mn system to enable the achievement of a balance between the coating performance required for a GA steel and the required mechanical properties.
- (2) Removal of the concentration of Si on the surface of CR TRIP steel sheets with the basic composition of C-Si-Mn ensured the level of e-coat performance for automotive use.
- (3) An identical level of formability has been achieved in the 590 and 780 MPa class TRIP steels as that demonstrated by the conventional 440 and 590 MPa class HSS.
- (4) Spot welding strength was also verified as equivalent in the TRIP steels to the conventional steels.
- (5) The TRIP steels display excellent energy absorption properties, with an identical level of energy absorption to the conventional HSS at 10% lower weight.

- (6) The TRIP steels have been applied to the 2004 model year Odyssey, and will continue to be used in future Honda models. On average their use enables a reduction of 10 kg or more in weight per vehicle.

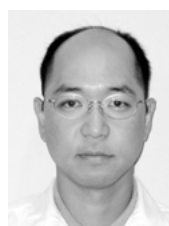
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