Ultra-High-Strength, Quench-type, Hot-Rolled Steel Sheets of 1,620MPa Grade for Automobile Door Impact Beams

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Higher-strength door-impact-beams (DIBs) are required as the regulations for side impact safety for automobiles become more stringent. Recently, an ultra-high strength, hot-rolled steel has been developed for this purpose. With its optimized chemical composition, the newly developed steel also exhibits excellent delayed-fracture resistance characteristics. DIBs made of the newly developed steel respond very well to crash situations and have a delayed-fracture resistance of 1,620 MPa. Applications for this newly developed steel are expected to grow.

Introduction

Stricter requirements are imposed on collision safety by newly revised regulations such as Federal Motor Vehicle Safety Standard (FMVSS) No.214 and Insurance Institute for Highway Safety (IIHS)[1]. To meet these requirements, there is a growing need for steels having super-high strengths. Ultra-high strength steels, having strength higher than 980 MPa, are now used for reinforcing members of automotive doors and bumpers.

This paper introduces a new quench-type, ultra-high strength steel of 1,620 MPa grade, developed for door impact beams. The steel is adapted for satisfying the requirements of stringent regulations set for side collision.

1. Requirements for door impact beams

Door impact beams are arrangements installed in vehicle doors to reinforce the doors against side collisions. A door impact beam (DIB) is designed to deform and thus absorb the kinetic energy of impact at an early stage of side collision, so as to reduce injury to occupants. **Photo 1** shows an example door impact beam installed in a vehicle door.

Press formed DIBs have conventionally been used[2], however, recent DIBs employ high-strength steel pipes for weight reduction[3]. The steels used for such pipes are made of either 1) ultra-high strength, cold-rolled steel sheets of 1,180 to 1,470 MPa grade, or 2) steel sheets heat-treatable after pipe making to 1,470 MPa grade. Furthermore, steel pipes of 1,620 MPa grade are being used. The requirements for such high strength steels include formability and weldability for pipe making and toughness after heat treatment as well as strength. Also required for such steel is a low susceptibility to delayed fracture. High strength steels are known to be prone to delayed fracture.

Photo 1 Example of door impact beam

2. The design concept of quench-type steel sheets for DIBs

2.1 The strength of quenched steel

Low alloy steel is preferable for workability and weldability. This is particularly true for quench-type steels for DIBs. The following describes the alloy design concept.

Table 1 shows the chemical compositions of the lab-scale steel samples tested. The steels were hot-rolled and ground to 2.0 mm thick plates. Each plate sample was soaked in a salt-bath at 900˚C for 3 minutes and then water quenched. The samples were machined into JIS #5 tensile test pieces and subjected to measurement. **Fig. 1** shows the results. The results show that C content in the steel has the largest contribution to the strength of steel having a martensite microstructure. The Mn and Si contents have less contributions than C content. The tensile strength (TS) is expressed by the following formula:

$$TS\ (MPa) = 4000 \times [\%C] + 100 \times [\%Mn] + 50 \times [\%Si] + 680$$

The C content was then adjusted to achieve

Table 1 Chemical composition of steels

(mass%)

C	Si	Mn	P	S
0.09 ～ 0.21	0.01 ～ 1	0.5 ～ 1.7	≦0.015	≦0.005

1,620 MPa strength. **Table 2** shows the chemical compositions of the samples. These steels are intended for use in DIBs which are subjected to electric resistance welding. At the time of welding, inadequate welding conditions may cause internals flaws, called penetrators, to form which are residues of oxides formed at the joint surfaces during welding. To prevent the formation of penetrators, Si and Mn compositions of the sample steels were selected to yield Mn / Si ratio of about 6 [5]. This is because the rather high Mn / Si ratio lowers the melting point of penetrators, facilitates discharge of oxides out of the system, and prevents oxides from remaining in the joint. In order to ensure hardenability, sufficient amounts of Cr and B were also added as well as Ti.

The steel samples of 2 mm thickness were soaked, quenched and tested in the same manner as described above. **Fig. 2** shows the results. The as-quenched strength increases with increasing C content and a strength of 1,620 MPa was found to be achievable with 0.20% C. The C content was thus set to 0.23% taking into account the variation during production.

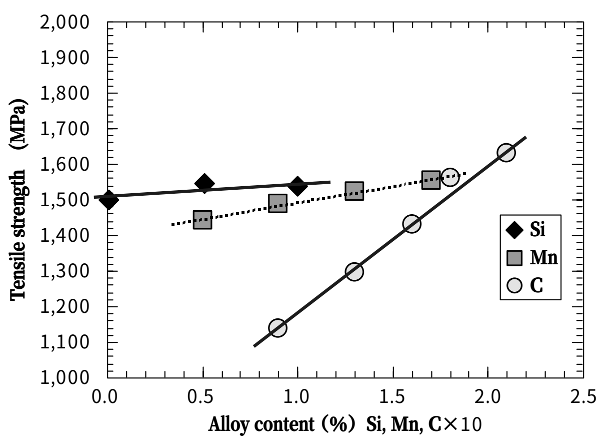


Fig. 1 Effects of alloy contents on tensile strength of quenched material

Table 2 Chemical composition of steels (mass%)

C	Si	Mn	P	S	Cr	Ti	B
0.16 ~ 0.34	0.22 ~ 0.28	1.25 ~ 1.35	0.010	0.005	0.20 ~ 0.25	0.020 ~ 0.030	0.0020 ~ 0.0030

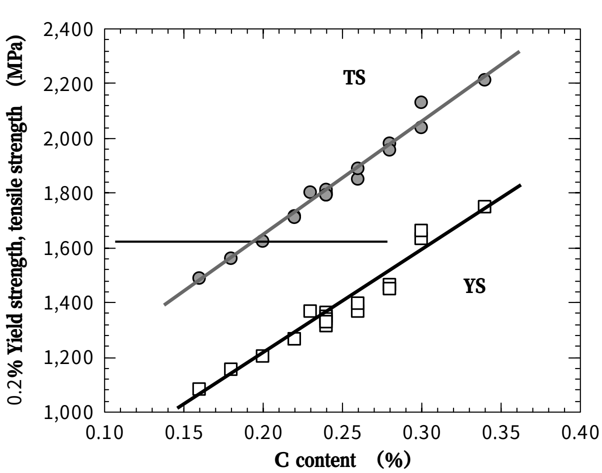


Fig. 2 Influence of carbon contents on tensile strength of quenched material

2.2 Delayed fracture characteristics

Steels with higher strengths are known to exhibit hydrogen embrittlement, or so called "delayed fracture"[6]. Ultra-High strength steel pipes may also suffer from delayed fracture caused by hydrogen generated by corrosion reaction with ambient environment.

Hydrogen is considered to diffuse into steel, concentrate at a location where tensile stress is higher, and causes embrittlement at that location. The mechanism of hydrogen embrittlement has not been elucidated yet, although several theories have been proposed, including, for example, "pressure theory"[7] and "the reduction of binding force between iron atoms"[8]. In general, however, hydrogen embrittlement of a steel is considered to be a phenomenon in which three factors interact with each other, i.e., I) absorbability of hydrogen into the steel; II) diffusivity of hydrogen in the steel; and III) susceptibility of the steel to embrittlement.

Therefore, three measures are considered to be effective in preventing hydrogen embrittlement of high-strength steel, i.e., 1) preventing the penetration of hydrogen into the steel; 2) suppressing the diffusion and local concentration of hydrogen to a tensile-stressed region; and 3) making the steel itself less susceptible to hydrogen embrittlement. Many attempts have been made so far for achieving the above measures 2) and 3), however, this newly developed steel also accounts for the measure 1). The hydrogen absorption of steel occurs during corrosion of the steel in an ambient environment. Hydrogen generated by such corrosion may not be released as a gas but may penetrate into the steel. Therefore, improving the corrosion resistance of the steel should prevent hydrogen absorption and achieve the measure 1). In addition, improved corrosion resistance prevents uneven corrosion of steel surfaces and thus reduces stress concentration. Based on this concept, Kobe Steel identified Cu as an effective alloying element for achieving the above measure 1).

Steels containing various amount of Cu were prepared into lab-scale rolled sheets of 2 mm thickness. The rolled sheets were heat-treated in a salt-bath to obtain strip specimens with a tensile strength of 1,780 MPa. The strips were U-bent with a bending radius of 5 mm. The bending direction was set parallel to the rolling direction as shown in **Fig. 3**[9].

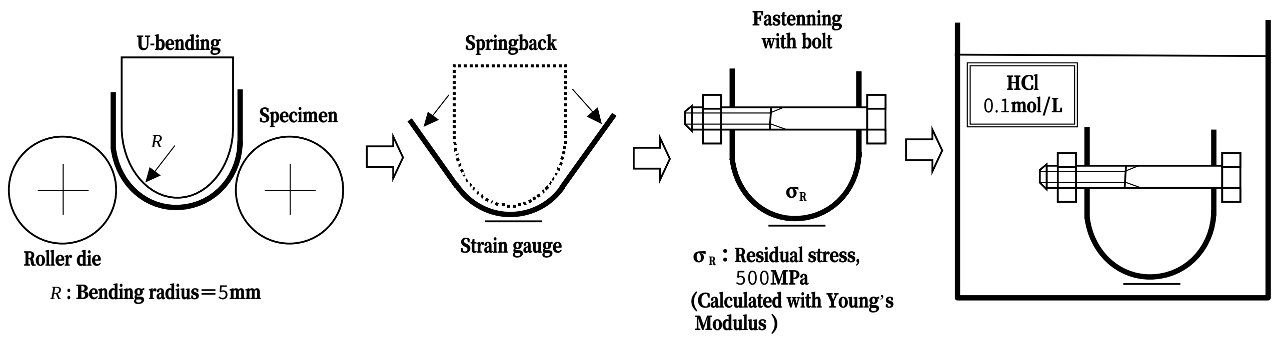


Fig. 3 Experimental procedure of delayed fracture resistance test

Each of the bent specimens was bolted to bear a load of 500 MPa as measured by a strain gauge attached to the bent portion. The bending is to simulate the stress condition created by pipe making. Each of the bolted samples was then immersed in a 0.1 mol/L solution of hydrochloric acid to evaluate its susceptibility to delayed fracture[4]. After immersion for 336 hours (14 days), the specimens were inspected for cracking and the results are shown in **Fig. 4**. The results show that Cu is a very effective element in preventing delayed fracture.

The effect of Cu is attributable to the equilibrium potential of steel containing Cu being more positive, which shifts its anodic polarization curve in the noble direction and prevents the dissolution of iron. At the same time, Cu addition is considered to increase the hydrogen overpotential, suppress the cathode reaction, reduce the amount of hydrogen penetrating into the steel and thus improve the delayed fracture characteristic. That is:

Anode: $Fe \rightarrow Fe^{2+} + 2e^-$

Cathode: $H^+ + e^- \rightarrow H_{ads}$: Hydrogen adsorbed

$2H_{ads} \rightarrow H_2(gas)\uparrow$

$2H_{ads} \rightarrow H(s)$: Hydrogen penetrating

In addition, Cu in steel forms a densely packed rust layer which prevents further rusting and/or rust-spalling and thus prevents corrosion. The improved delayed fracture characteristic is considered to be a combined effect of these behaviors.

A small addition of Cu improves the delayed fracture characteristic of quench-type, high-strength steel of 1,620 MPa grade in the manner described above.

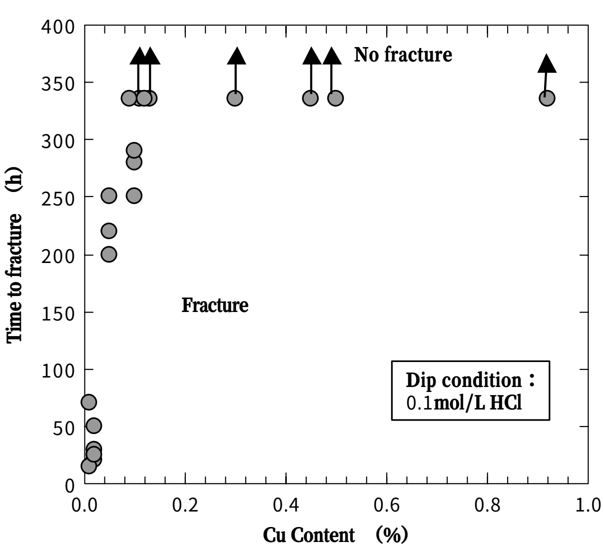


Fig. 4 Influence of Cu content on delayed fracture

3. The properties of quenched steel pipes

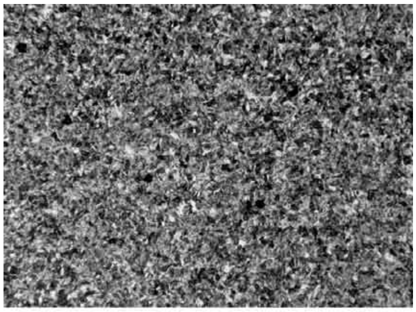
Based on the lab-scale results, hot-rolled sheets, each having a thickness of 1.6 mm, 1.8 mm and 2.0 mm, were produced in an actual production line. **Table 3** shows the chemical compositions of the steels. The steel sheets were electric-resistance welded into pipes having an outer diameter of Φ31.8 mm. The pipes were subjected to high frequency induction quenching and finished into quenched DIBs. The mechanical properties of the pipes are also shown in Table 3. The microstructure of a quenched steel pipe is shown in **Photo 2**-a). Photo 2-b) shows the prior austenite grain boundary of the same sample. The heat-treated pipe shows predominantly a fine martensitic structure.

The steel pipes were subjected to three-point bending tests as shown in **Fig. 5**. The method is based

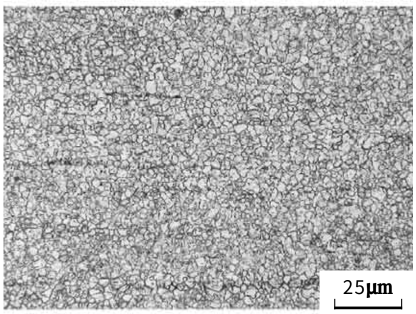
Table 3 Chemical composition and mechanical properties of steels

(mass%)

Steel	C	Si	Mn	P	S	Cu	Al	Cr	Ti	B	YS (MPa)	TS (MPa)	El. (%)
Steel A	0.20	0.21	1.25	0.010	0.004	0.10	0.038	0.20	0.027	0.0025	1203	1625	12.5
Steel B	0.23	0.20	1.26	0.011	0.003	0.12	0.042	0.21	0.028	0.0028	1369	1801	12.7



(a) Martensite suructure



(b) Austenite structure

Photo 2 Optical micrographs of heat treated pipe

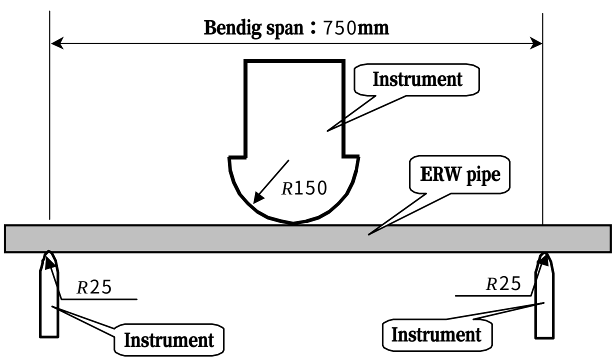


Fig. 5 Experimental procedure of bending test

on the side door testing procedure for vehicle side collision (JASO B 103-86). The resulting load/displacement curves are shown in **Fig. 6**. The absorbed energies were calculated from the curves for displacements up to 150 mm. **Fig. 7** depicts the relationships between the plate thickness, bending load and absorbed energy. Both the maximum bending load and absorbed energy increase with increasing plate thickness, and are further increased by strengthening of the steel pipes.

Impact tests were also performed on the pipes to evaluate their low temperature toughness. Test pieces, each having a V-notch of 2mm (JIS #4 impact test piece), were prepared from the quenched pipes. **Fig. 8** shows the change in the brittle fracture ratio with test temperature. In general, toughness is largely affected by material hardness and the brittle fracture transition temperature (vTrs) tends to become higher with increased material strength. However,

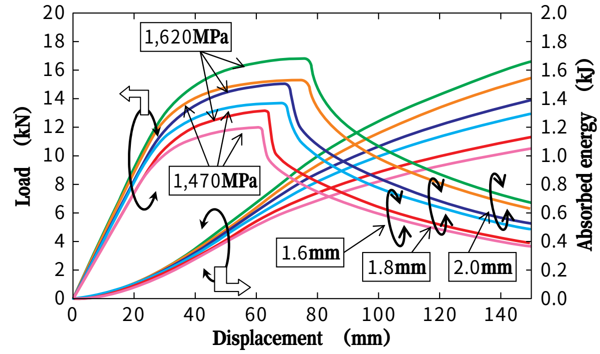


Fig. 6 Effects of TS and thickness on bending load and absorbed energy of quenched pipes

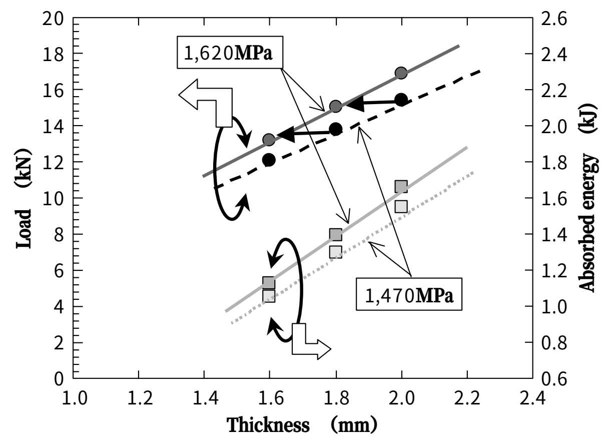


Fig. 7 Relationship among bending load,absobed energy and pipe thickness

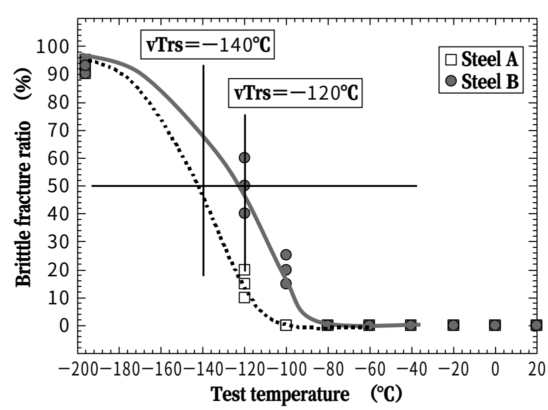


Fig. 8 Relationship between testing temperature and brittle fracture ratio

the newly developed ultra-high strength steel has a brittle fracture transition temperature (-120˚C) comparable to that of a 1,470 MPa grade steel.

The pipes are also immersed as-is in a 0.1 mol/L hydrochloric acid solution for delayed fracture characterization. No crack was observed after 336 hours of immersion. The developed pipes satisfy all the properties required for DIBs.

Conclusions

A newly developed quench-type, ultra-high strength steel of 1,620 MPa grade has been introduced. The steel is very suitable for door impact beams (DIBs) to provide impact resistance to side collision.

The low alloy steel provides strength, toughness, fracture behavior and weldability required for quench-type DIBs. The developed steel of 1,620 MPa grade is now used as the material for DIBs satisfying all the requirements from customers.

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