

Development of High-strength Structural Steel for Welding

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ABSTRACT

A high-strength structural steel that enables pre-heating and post-heating to be omitted from the welding procedure without the occurrence of weld cracks has been developed. A process has been developed that enables the achievement of an equivalent level of strength and toughness to alloy steels for machine structural use while omitting the quenching process, through the partial application of modified ausforming, in which, immediately following processing during the hot forging process, the material is rapidly quenched at the unrecrystallized austenite temperature just above the A3 transformation temperature.

1. Introduction

Efforts are progressing to reduce CO₂ emissions as a means of controlling global warming. Automobiles account for 18% of CO₂ emissions in Japan, and technological development to reduce CO₂ emissions, including the development of various technologies to increase fuel efficiency and the rationalization of production processes, is active in the country. In the area of body components, efforts are being made to achieve weight savings by increasing the strength and reducing the number of parts, and to reduce sliding resistance and rolling resistance.

The project discussed in this paper focused on a technology to achieve weight savings. It attempted to reduce the number of parts used by enabling direct welding of forged steel parts. These parts have previously been bolted together, because welding has represented a challenge. In order to achieve its goal, the project developed a weldable forged steel without sacrificing strength.

The first issue to be considered during welding is the occurrence of weld cracks. The occurrence of weld cracks is influenced by the chemical composition of the steel, and reduction of the carbon content in particular assists in preventing them. However, the strength of the steel is

influenced by its chemical composition and its microstructure, and reduction of carbon content tends to reduce strength. In high-strength steel plates, control of weld cracks and the achievement of a high level of strength have been achieved by reducing the carbon content and applying a variety of heat treatments to strengthen the microstructure of the material⁽¹⁾. However, forged parts are thicker than steel sheets. Given that it is challenging to control their internal temperature, and from a cost perspective, there are restrictions on the ability to achieve high strength by means of the microstructure of the material. Because of this, the dependence of both weldability and strength on chemical composition is high in forged parts, and the range of choices available to reconcile these parameters is more limited than it is in the case of steel plates. In addition, thick parts tend to be harder on the surface than in the interior. This makes it necessary to increase strength in order to offset this reduction in internal strength, making it more challenging to guarantee weldability.

In order to reconcile surface strength and weldability, the project discussed here addressed these issues through the development of a forged steel displaying a level of hardenability not previously achieved, and which also demonstrated internal strength. At the same time, the project also focused attention on the production process;

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the use of the heat of the hot forging process for quenching has enabled the quenching process to be abbreviated, reducing CO₂ emissions during production.

2. Development Concept

2.1. Study of Chemical Composition

One cause of weld cracks is the fact that the hardness of welded areas becomes excessively high in comparison to the surrounding area. The project therefore attempted to determine a chemical composition for the new material that would help prevent this excessive hardness despite welding, and which would produce only a minimal decline in internal hardness.

2.1.1. Controlling weld cracks

Equation (1), specified by the Japan Welding Engineering Society in WES 3001, shows the relationship between the occurrence of weld cracks and chemical composition in terms of the weld crack parameter (Pcm). The symbols in Eq. (1) show the amount of each element added in terms of mass%.

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (1)$$

Past results indicate that the Pcm should be no greater than 0.29 in order to help prevent weld cracks without preheating or postheating.

2.1.2. Maintaining hardness

It is reported that the potential danger of weld cracks occurring increases if the maximum hardness of the welded area exceeds 400 HV (corresponding to 41 HRC)⁽²⁾. Because the welded areas would be quenched microstructures, the quenching hardness was set at 400 HV or lower. The size of almost all forged parts used in automobiles, in terms of conversion to the diameter of a round rod, is 30 mm or less. Given this, the critical diameter, as specified by JIS G 0201, was set at 30 mm or more.

The following considerations were applied to achieving the highest temper hardness possible. Because machining is the final stage in the process of manufacturing a part from forged steel, a hardness of 38 HRC or less is therefore generally considered desirable from the perspective of tool life. In addition, in order to help prevent the brittleness associated with low-temperature tempering, the tempering temperature should be set at 400°C or higher. This led to the goal of achieving the highest level of hardness possible under 38 HRC at a tempering temperature of 400°C.

Adjustment of the chemical composition on the basis of these conditions produced the formula shown in Table 1. In comparison to conventional steels used in forging, the composition is noteworthy for its low carbon content and the high level of manganese that it contains.

Table 1 Chemical composition of developed steel (mass%)

	C	Si	Mn	P	S	B	Ti
Upper bound	0.15	0.3	2.2	0.03	0.03	0.003	0.07
Lower bound	0.10	-	1.4	-	-	0.001	0.03

2.2. Study of Manufacturing Process Enabling Abbreviation of Quenching Procedure

Direct quenching from forging temperature is a manufacturing method in which the steel is quenched directly after hot forging. This is an effective technique from the perspective of efficient use of heat, but involves quenching from the high temperature (around 1200°C) used in the hot forging procedure, which causes the crystal grains in the material to increase in size, resulting in reduced toughness, compared to normal quench tempering. Modified ausforming⁽³⁾, in which quenching is conducted after forging in the unrecrystallized austenite temperature above the A3 transformation temperature, is known as a method enabling the achievement of high toughness in hot forging, but the low forging temperature employed in the method increases the forging load, resulting in reduced die life. However, it was conjectured that the forging load could be reduced and a high level of toughness achieved in the component by employing modified ausforming only in the sections of the parts where stress concentrated.

3. Test Method

Table 2 shows the heat patterns tested in this project. In Pattern A, the steel was subjected to modified ausforming (water quench [W.Q.] from process Fo2) and tempering following hot forging (process Fo1). Patterns B and C were employed as comparisons. In Pattern B, the steel was quench-tempered following hot forging, while in Pattern C the steel was tempered following forge quenching. Using these heat patterns, the mechanical properties of test pieces formed by forward extrusion, with an area reduction ratio of 30%, and the internal hardness and microstructure of test pieces forged in a die corresponding to a mass production die, were studied. In the case of the forged test pieces for Pattern A, Fo1 and Fo2 were conducted at the same time as weld flash removal, using a hammer forger for the former and a trimming press for the latter. Conducting processes Fo1 and Fo2 on different apparatus helped to ensure that the cooling time between the processes did not affect the tact time for the parts.

Hardenability was studied using the JIS G 0561 Jominy end quench test. In addition, their softening curves

Table 2 Heat pattern

Pattern A	Pattern B	Pattern C

were measured.

Tensile tests using JIS Z 2201 14B tensile test pieces and Charpy impact tests using JIS Z 2202 U-notch Charpy test pieces were conducted in order to study mechanical properties.

To study weldability, strength and fracture position were evaluated using test pieces arc welded to form a lap joint between parallel sections, as shown in Fig. 1. In addition, Vickers hardness tests were conducted to determine the hardness distribution close to the welded sections in the matrix, which had an average hardness of 260 HV. Thirty-five HRC test pieces were formed from steel containing upper limit amounts of the chemical components, which had been quenched at 900°C and tempered at 425°C following sheet rolling to a thickness of 3 mm, with 440 MPa class steel sheets used as the welding rods.

To determine machinability, test pieces of the type shown in Fig. 2 were drilled until the drill broke, and tool wear for the prescribed number of holes was evaluated.

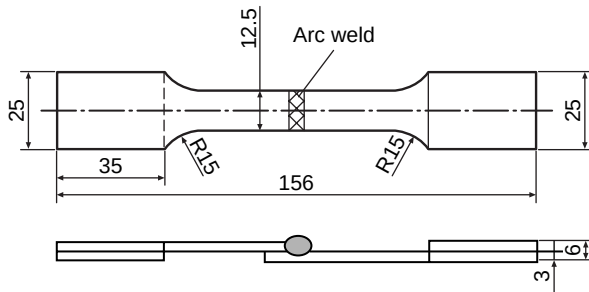


Fig. 1 Weldability test piece

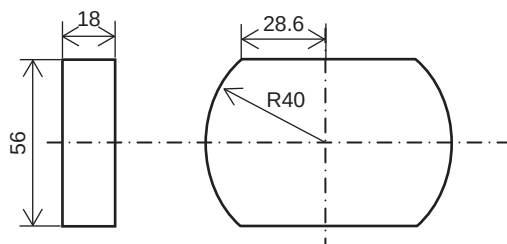


Fig. 2 Machinability test piece

4. Test Results

4.1. Test Results for Test Pieces

4.1.1. Hardenability

The Jominy curve of the developed material is shown in Fig. 3. For comparison, the Jominy curves of a representative carbon steel (S48C) and alloy steel (SCM435H) for machine structural use are also shown. At the lower limit set for chemical components, the steel achieved a maximum hardness of 38 HRC following quenching, and the distance from the quenched end to the point at which the hardness increase of the surface against the interior was halved was 18 mm. Converted to critical diameter⁽⁴⁾, this represents a diameter of more than 70 mm, indicating the achievement of a sufficient level of hardenability.

4.1.2. Temper softening curve

The temper curve of the developed material is shown in Fig. 4. The hardness of the material following tempering at 400°C was 37 HRC at the upper limit for chemical components, and 35 HRC at the lower limit. The material can therefore be used at 37 HRC and below.

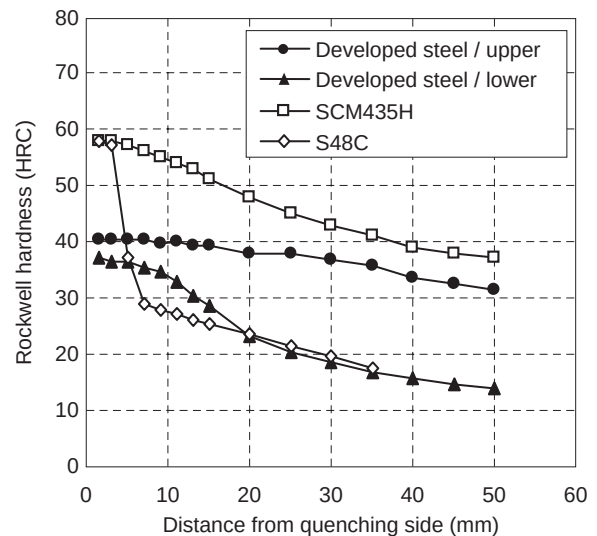
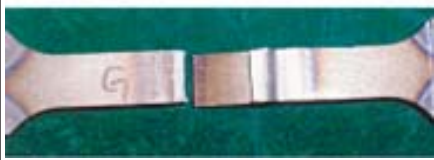


Fig. 3 Jominy curve

Table 3 Mechanical properties of developed steel

	Heat treatment	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Charpy impact value (J/cm ²)
Upper bound	Pattern A	898	941	23.1	220
	Pattern B	876	949	22.0	201
	Pattern C	873	943	21.9	160
Lower bound	Pattern A	880	911	22.8	260
	Pattern B	850	905	22.1	245
	Pattern C	873	932	22.0	230

Table 4 Fracture behavior of tensile test piece containing welding bead

	Appearance after tensile test	Fracture position	Tensile strength (MPa)
Upper bound		HAZ	673
Lower bound		HAZ	520

4.1.3. Mechanical properties

The mechanical properties of the developed material are shown in Table 3. The highest Charpy impact value was obtained for Pattern A. Even in the case of Pattern C, which resulted in a decline in the Charpy impact value, a value of 160 J/cm² or higher was obtained. This is higher than the value for S48C and equivalent to that for SCM435.

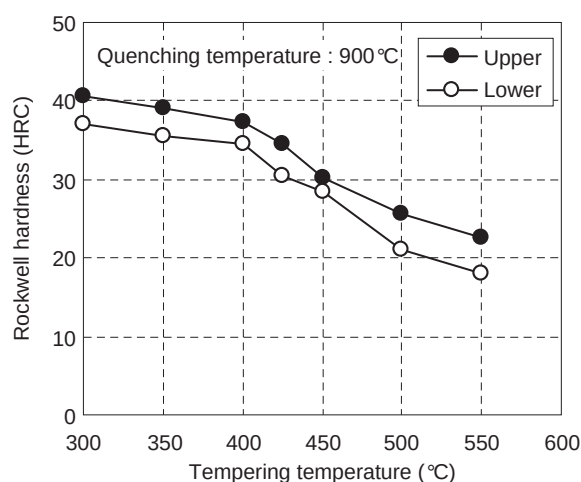


Fig. 4 Temper softening curve

4.1.4. Weldability

Table 4 shows the results of tensile tests on test pieces containing welding beads. The tests showed that fractures occurred in the heat-affected zone (HAZ), and that there was no incidence of welding cracks. X-ray analysis and penetrant inspection also showed no incidence of welding cracks.

The microstructure of the material and the hardness distribution around the welding beads are shown in Fig. 5. While the matrix is tempered martensite, the white corroded section at the boundary of the HAZ exhibits a mixed bainite-ferrite microstructure, with a martensite occurring further into the interior. The hardness of the area in the bainite-ferrite microstructure that shows the maximum decline in hardness is 250 HV, almost identical to the hardness of the matrix.

4.1.5. Machinability

Figure 6 shows changes in levels of tool wear at different levels of hardness, as determined by the drill life test. The graph also contains data for an alloy steel for machine structural use. The results show that the developed steel achieves an equivalent level of machinability to the alloy steel. While the developed material contains a high quantity of manganese, which would tend to reduce machinability because of its effect in increasing working hardness, it is thought that this

effect is offset by the reduction in the content of carbon, which has a greater effect on hardness.

4.2. Result of Tests on Parts

4.2.1. Mechanical properties and internal microstructure

The developed material was evaluated as a rear

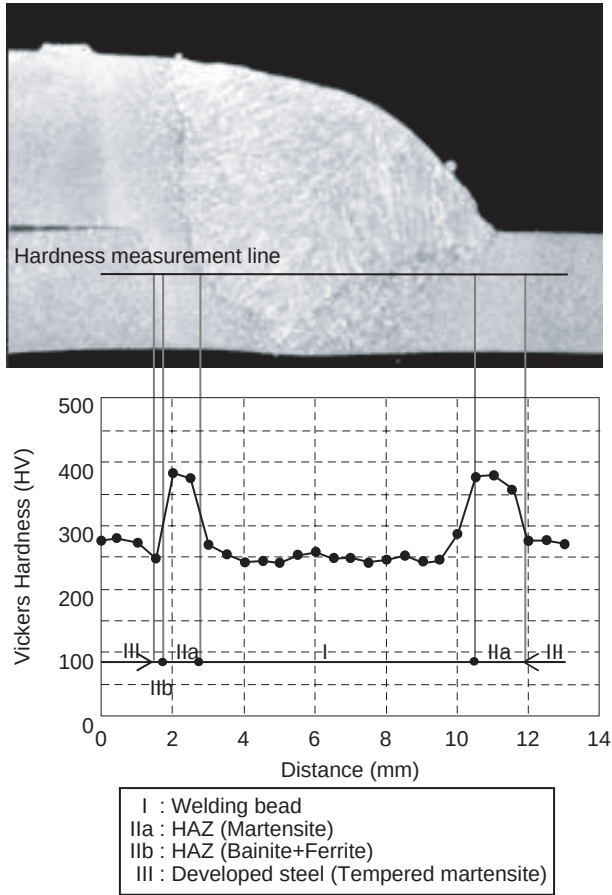


Fig. 5 Microstructure and hardness distribution around welding bead

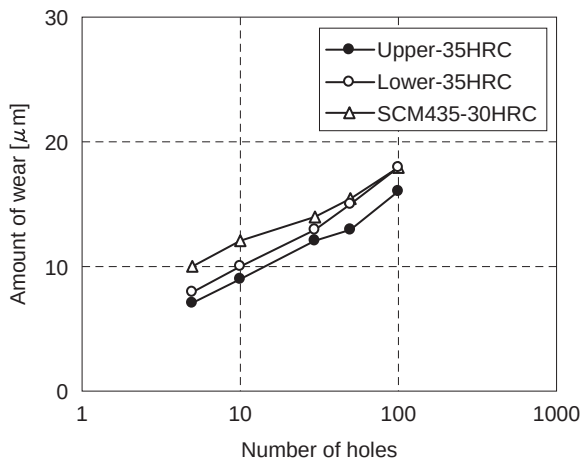


Fig. 6 Relationship between amount of wear of twist drill and hardness

spindle in order to provide an example of its application in a part. Figures 7 and 8, respectively, show the rear spindle and the layout of parts around the rear spindle. This part supports the driven wheels on the axle beam, and therefore should display high levels of both strength and toughness. Figure 9 shows the hardness distribution in the spindles manufactured for the test. There was almost no difference in hardness for the different heating patterns, and the hardness distribution was almost uniform, with only a two-point difference in hardness between the surface and the



Fig. 7 Rear spindle

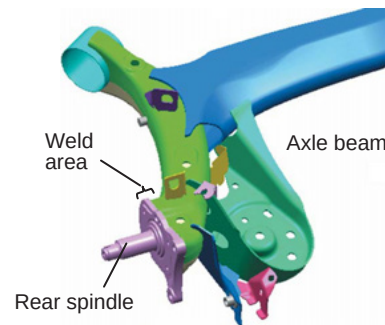


Fig. 8 Parts layout around rear spindle

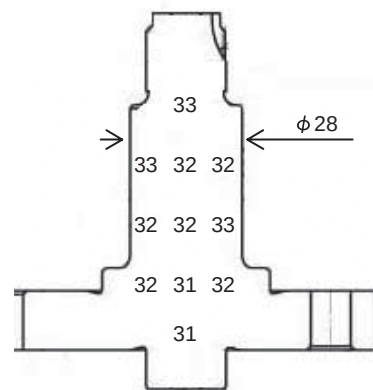


Fig. 9 Hardness distribution of rear spindle

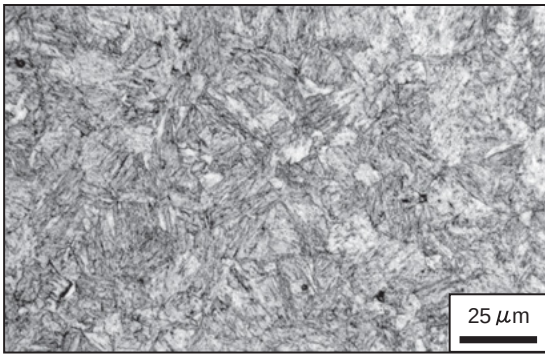


Fig. 10 Microstructure of rear spindle center

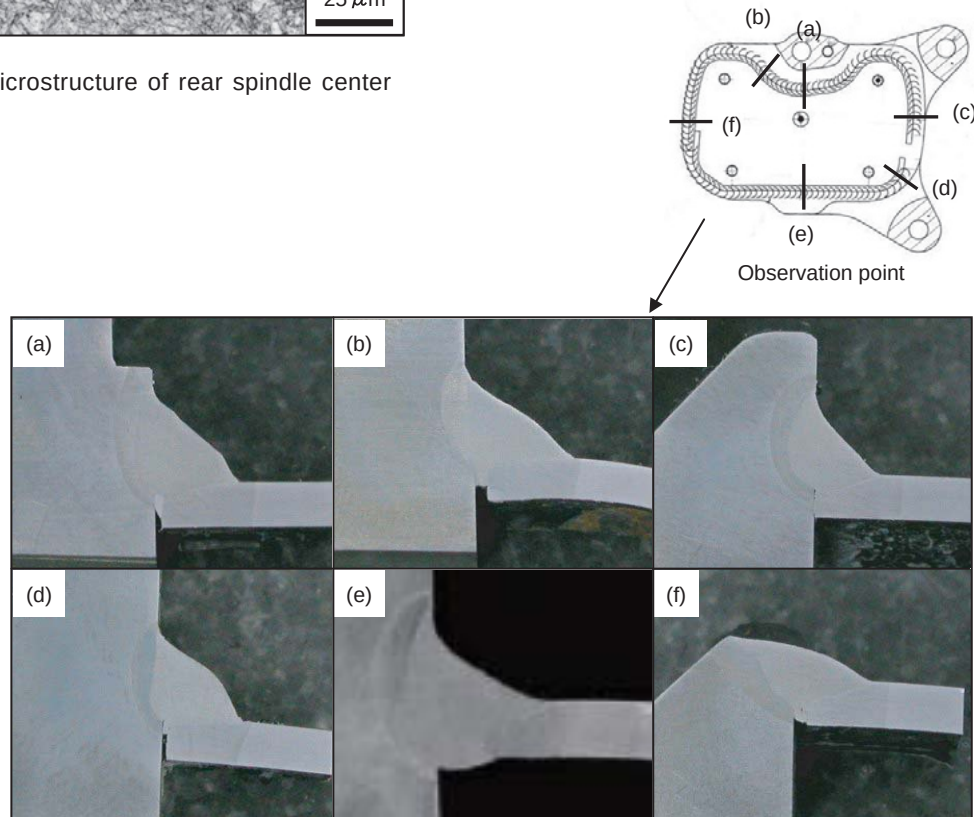


Fig. 11 Microstructures around welding beads of rear spindle

center of the part. Figure 10 shows the microstructure of the center of the spindle. A good tempered martensite microstructure has been achieved up to the center.

4.2.2. Weldability

Figure 11 shows the position and the microstructure of the welding beads between the rear spindle and the axle beam. The axle beam was manufactured from 440 MPa class hot-rolled steel plates, and 440 MPa welding wire was employed. A good bead shape was achieved, with no weld cracks or penetration issues. A variety of strength and durability tests were conducted on the structure, and no failure originated in the welding beads.

5. Conclusion

A weldable high-strength structural steel has been developed. In addition, the application of modified ausforming to sections of parts has enabled the quenching process to be abbreviated during manufacture. The characteristics of the developed steel are as follows:

- (1) The steel can be arc welded without preheating or postheating.
- (2) Quench tempering enables the achievement of a hardness of 37 HRC; the critical diameter for quenching is 70 mm and higher.
- (3) The Charpy impact value of the steel is 160 J/cm² or above.
- (4) The machinability of the steel is equivalent to that of an alloy steel for machine structural use.

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