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Shear Reinforcement Possessing both of Over 1 275 MPa Yield Strength and High Ductility after Welding†

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Abstract:

JFE Steel has developed the high strength shearing reinforcement that reduced the softening induced by heat during welding. The purpose of reducing the softening is to prevent the deformation concentration on the softened area. Softening by the heat effect was the maximum when the steel was heated up to 700–750°C. The most softened area corresponds to the area heated up to the highest temperature where austenite does not exist in the microstructure. Hardness in the heat-affected zone is raised with the increase of the amount of Mo, V. When the difference in Vickers hardness between the most softened area and the base steel is 70 or less, it breaks at the base steel, which has high ductility, even after welding. High strength has been united to excellent ductility by controlling the hardness distribution in the heat-affected zone after welding.

1. Introduction

Reinforcing steel in reinforced concrete (RC) can be broadly divided into main reinforcement in the height direction of the structure and shear reinforcement (hoop reinforcement) placed at approximately right angles to the main reinforcement. In earthquakes, the role of the shear reinforcement is to prevent the concrete from reaching a state of brittle shear fracture due to the bending stress generated in the columns and beams. Accompanying the trend toward RC construction in high-rise buildings, recent years have seen an increasing number of examples in which high strength reinforcing steel was adopted not only in the main reinforcements, but also in the shear reinforcements, resulting in heightened demand for high strength steel bars1).

Shear reinforcement possessing yield strength of the 1 275 MPa class is the highest strength steel currently adopted. High strength is obtained in this steel by forming tempered martensite, which is achieved by quenching and tempering steel having the proper carbon content.

As shown schematically in **Fig. 1**, the construction methods used with shear reinforcement can be broadly classified into two types, one being the spiral type, in which the shear reinforcement is arranged by wrapping the hoops around the main reinforcement in a spiral shape and securing the hoops with hook-shaped parts at its ends, and the welded type, in which a series of individual hoops is arranged in parallel around the main

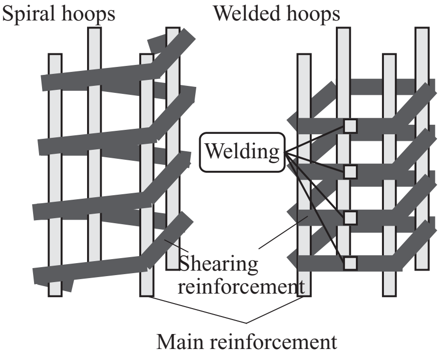

Fig. 1 Schematic illustration of shear reinforcement arrangement

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reinforcement, and each hoop is closed by welding[2)].

The welded type is advantageous from the viewpoint of workability, for example, convenience in transportation of the reinforcing steel, ease in construction of beams, etc. However, when conventional high strength steel bars of 490 MPa class and higher are welded, softening of the heat-affected zone (HAZ) occurs. This is a problem because the strength of the welded joint decreases to a lower level than that of the base material, and ductility is reduced due to the concentration of deformation in this softened area.

Focusing on this condition, the aim in this development was to develop a YS1275 MPa class shear reinforcement that can also be applied to welded type shear reinforcements.

2. Concept of Development

Upset welding is a typical resistance welding method for welded type hoop reinforcements. A schematic image of the welding process is shown in **Fig. 2**, and the appearance of a welded bar immediately after welding and after deburring is shown in **Photo 1**.

Photo 2 shows an example of the macrostructure of the longitudinal section around an upset weld, **Fig. 3** shows the hardness distribution corresponding to the distance from the bonding interface, i.e., around the HAZ, and **Fig. 4** shows the maximum temperature achieved in each part during upset welding when using deformed steel bar (rebar) possessing YS1275 MPa or higher manufactured by quenching and tempering low alloy steels without addition of alloying elements such as Mo, V, etc. When welding is performed on a steel having a tempered martensite microstructure, the bonding interface where melting and solidification occur and its surrounding area are exposed to high temperatures in excess of 800°C, and austenite is formed during heating. When this area is rapidly cooled at the end of welding, a

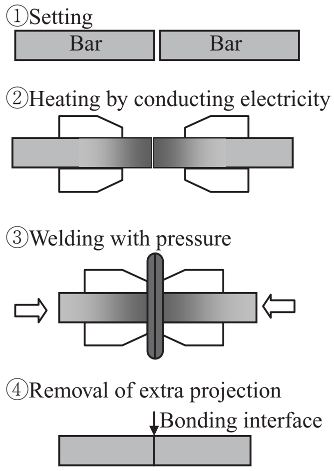


Fig. 2 Schematic image of the process of upset welding

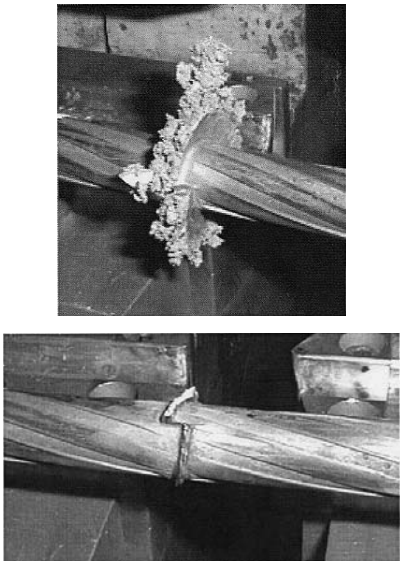


Photo 1 Externals of welded bar

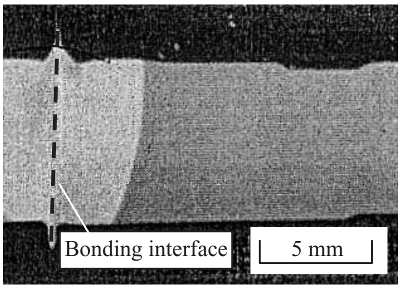


Photo 2 Macrostructure of longitudinal section of the steel after upset welding

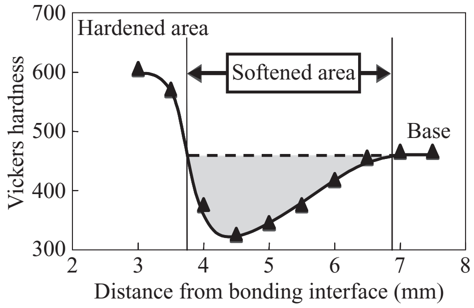


Fig. 3 Hardness distribution around heat-affected zone after upset welding in low-alloyed steel

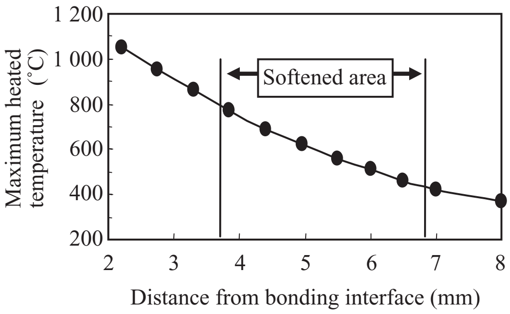


Fig. 4 The maximum heated temperature of each part during upset welding

hard phase of martensite forms once again, resulting in higher hardness than in the base material. Conversely, in parts located at a certain distance from the bonding interface, the temperature during welding is less than 700°C. In this temperature region, tempering progresses further than in the base material, forming a softened area which is softer than the base material.

If tensile stress is applied to a low alloy steel having this kind of hardness distribution, deformation will concentrate in the softened area, the strength and ductility of this area will be remarkably deteriorated in comparison with the base material, and it will be impossible to obtain the specified strength characteristics.

As a countermeasure for this problem, the cross-sectional area is increased so as to compensate for the reduction of the strength in the welded joint. This is accomplished by designing the maximum diameter of the joint to be at least 1.4 times greater than the diameter of the base material, in other words, making the diameter of the softened area larger than that of the base material. However, when this measure is employed, the welded joint will have a protruding large-diameter bump at the joint. This causes various problems. In particular, because the cover thickness of concrete[3, 4] is specified in the Building Standards Law, AIJ Standard for Structural Calculation of Steel Reinforced Concrete Structures (AIJ: Architectural Institute of Japan), etc., it is necessary to increase the thickness of the concrete as a whole order to secure the required cover thickness of concrete at the parts having this protruding shape, and this increases the volume of the columns and beams concerned.

Therefore, in this research, the authors focused on suppressing softening of the HAZ during welding of the reinforcing steel with the aim of maintaining an excellent bump-free welded joint shape and preventing concentration of deformation in the softened area of the HAZ. From this viewpoint, the key issues in this development were reducing the size of the softened area of the HAZ and increasing the minimum hardness.

3. Experimental Procedure

3.1 Test Steel

Table 1 shows the main chemical composition of the sample steel which was used in order to investigate the effects of alloying elements on temper softening resistance. The base composition was a steel in which Si, Mn, and Nb were added to 0.28 mass% C steel. Using this base steel, the amounts of added Cr, Mo, and V were varied in order to investigate the effects of these elements on the properties of the material. These test steels were prepared by vacuum melting and casting 30 kg ingots, followed by 2 heat hot rolling to plates with a thickness of 14 mm as materials for property evaluations. These materials were machined into cylinders with a diameter of 12 mm. High frequency quenching was performed by heating these specimens to 930°C, followed by adjustment of the tempering temperature of each steel to obtain a tensile strength of 1 450 MPa.

Table 1 The chemical composition of steel examined

(mass%)

C	Cr	Mo	V	Others
0.28	0.70–1.20	0.10–0.45	0.01–0.25	Si, Mn, Nb

3.2 Measurement of Softening Resistance

Softening of quenched and tempered steels after welding is considered to be caused by high temperature tempering of the HAZ. In order to reproduce the heat history during welding, reheating tests were performed using a heat treatment simulator (Formastor, manufactured by Fuji Electronic Industrial Co., Ltd.). Test pieces with a diameter of 3 mm and length of 8 mm were machined from the above-mentioned materials after high frequency quenching and tempering. These specimens were then held at 700–850°C using the heat treatment simulator, and their hardness after this treatment was investigated.

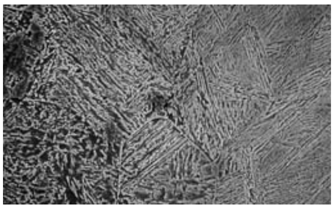
3.3 Investigation of Relationship between Softening after Welding and Low Ductility Fracture

Steels of the same compositions as several of the test steels were melted and cast into 100 kg ingots, which were then rolled to 150 mm square. Wire rod material with a diameter of 14 mm was obtained from these materials by wire rod rolling, and materials for evaluation were obtained through a process from drawing to high frequency quenching and tempering using commercial equipment. Actual upset welding was performed using these materials. Tensile tests were performed on the welded specimens, and the occurrence of low ductility fracture in the test and the hardness distribution around the welds were arranged.

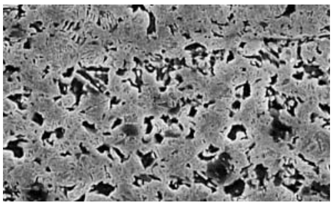
4. Experimental Results

4.1 Softening Behavior in Welding Heat Cycle Test

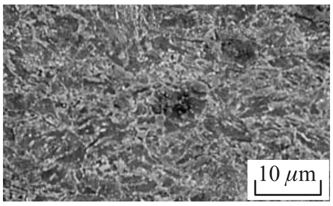
Examples of the microstructure and hardness of the test steels after the welding reproduction test are shown in **Photo 3** and **Fig. 5**, respectively. On the low temperature side, a decrease in hardness could be observed accompanying increases in the tempering temperature. However, hardness increased when the existence of martensite formed by rapid cooling after heating to the dual



Heated up to 800˚C Hv 606



Heated up to 750˚C Hv 568



Heated up to 700˚C Hv 400

Photo 3 Microstructure after reproduction test of welding using 0.28mass%C-0.7mass%Cr-0.1mass%V-0.35mass%Mo steel

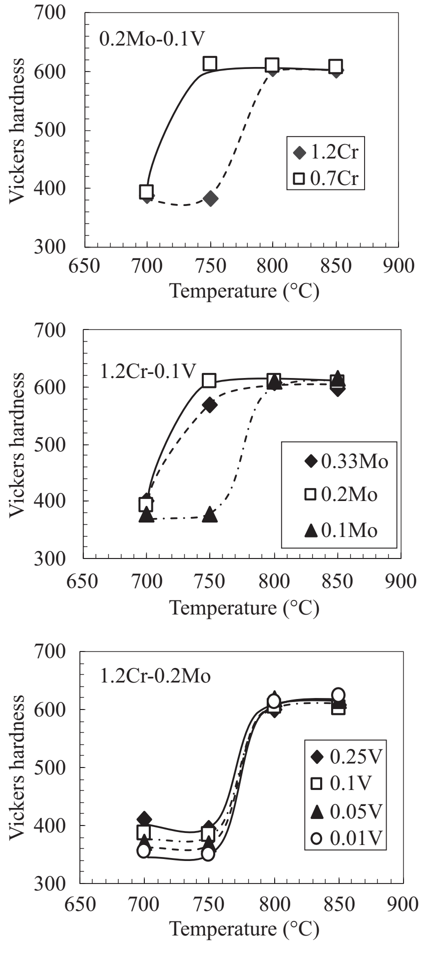


Fig. 5 Effect of temperature on the hardness of the steel after reproduction test of welding

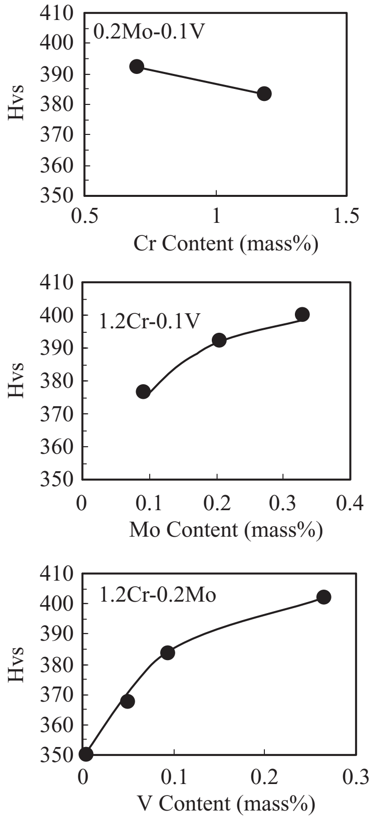


Fig. 6 Effect of alloy elements on the Vickers hardness at the most softened area (Hvs)

phase region could be detected in the microstructure, even when the martensite was present only in a trace amount. Although the results differed depending on the amount of alloy addition, the tempering temperature at which hardness showed the largest reduction was 700–750°C. The softest area is considered to correspond to the part which was heated during welding to around the maximum temperature in the ferrite region.

Based on the results shown in Fig. 5, the effects of the alloying elements on the hardness of the most softened area after the welding reproduction test were arranged as shown in **Fig. 6**. Because increased hardness in the most softened area was confirmed accompanying increased addition of Mo and V, addition of these elements was judged to be effective for improving welding softening resistance.

4.2 Relationship between Softening after Welding and Low Ductility Fracture

Figure 7 shows the effect of the hardness profile on the occurrence of fracture in the welding softened area. The area in which the hardness is reduced to a level below that of the base material is defined as the softened area. For each of the test steels, the width of the softened area was plotted on *x*-axis, and the difference between the hardness of the most softened part and that of the base material was plotted on the *y*-axis. The open circle

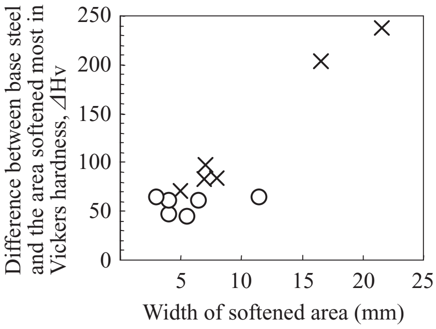


Fig. 7 Effect of the amount of softening and the width of softened area on the occurrence of breaking in softened area

marks (○) indicate high ductility fracture occurring in the base material, and the X marks show low ductility fracture occurring in the HAZ. Even after welding, breakage takes the form of high ductility fracture in the base material when the difference between the hardness of the most softened part and the base material ⊿Hv is 70 or less.

The Vickers hardness of base material corresponding to a yield strength of 1 275 MPa class (tensile strength: 1 420 MPa) is approximately 450 Hv. Thus, from these results, it can be understood that hardness of 380 Hv or more is necessary in the most softened part when subjected to high temperature tempering.

5. Features of Developed Steel

Based on the knowledge presented up to the previous chapter, a 1 275 MPa class high strength steel bar and 1 275 MPa class welded type steel reinforcement “Riverbon (trademark registration No. 1400177)” with extremely high softening resistance and excellent welded joint shape were developed and commercialized by suppressing softening of the weld, which had been a problem with the conventional high strength steel bars. In the developed steel, softening originating in the HAZ was successfully controlled by selecting appropriate alloying elements such as Mo, V, etc. and optimizing the amount of addition.

Figure 8 shows the hardness distribution around the HAZ after upset welding in the developed steel and the previous low alloy steel. As distinctive features of the developed steel, the decrease in hardness in the softened area is extremely small, and the width of the softened area is also narrow. **Figure 9** shows the strength-elongation balance of high strength shear reinforcements manufactured using the developed steel and a low alloy steel before and after welding. Based on the aforementioned effect of the HAZ hardness distribution, the high strength shear reinforcement using the developed steel achieves an excellent strength-elongation balance without the countermeasure of increasing the maximum diameter of the joint, as described previously.

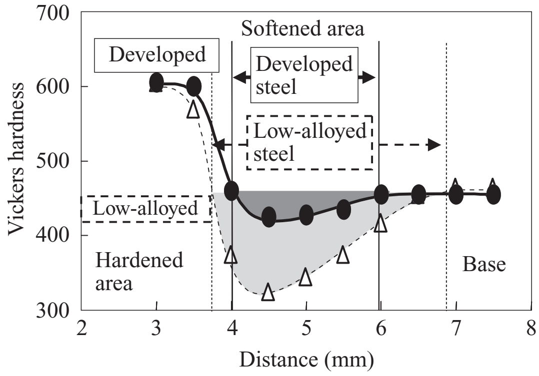


Fig. 8 Hardness distribution around heat-affected zone after upset welding of developed steel and low-alloyed one

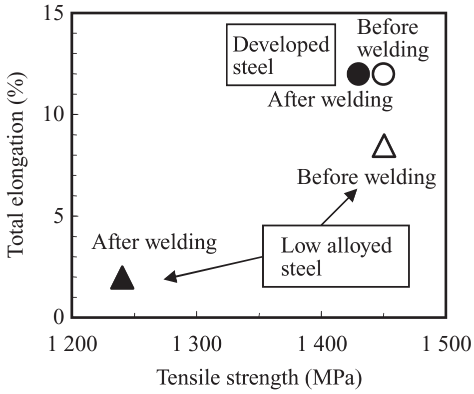


Fig. 9 Tensile property balance in the steel before and after welding

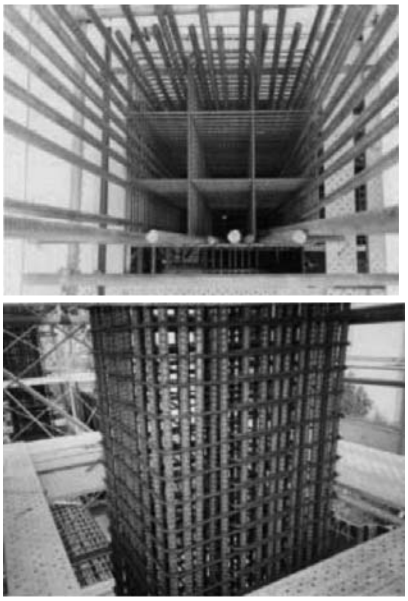


Photo 4 Examples of constructions using developed steel

Examples of construction using the developed steel are shown in **Photo 4**. Because the diameter of the welded joints can be made substantially the same as that of the base material, the developed steel demonstrates its effectiveness, particularly in RC structures. For example, due to the excellent welded joint shape, which is free of protruding parts, the required cover thickness of concrete specified in the Enforcement Order of the Building Standards Law is easily secured, making it possible to obtain the merits of a compact cross section in the columns and beams.

6. Conclusion

In order to prevent brittle fracture as increasingly high strength concrete is applied to meet the requirements of taller concrete structures, use of higher strength shear reinforcements in combination with higher strength concretes is effective. On the other hand, as the strength of the shear reinforcements increases, low ductility fracture accompanying softening of the HAZ during welding becomes a problem. To solve this problem, the effects of Mo, V, and other alloying elements and the amount of alloying element addition on softening of the HAZ were investigated. By adopting a composition design based on the results of this study, it was possible to minimize the decrease in the hardness of the softened part due to the effect of heating during welding, and also to control the range of the softened part to a narrow width. As a result, a new steel with an excellent balance of tensile strength and elongation after welding was successfully developed. In the future, JFE Steel and JFE Techno-wire will continue to study and develop high strength shear reinforcements matched to the higher strength of concrete.

References

1) Shibata, Masataka; Nakazawa, Atsushi; Shiraishi Tamaki; Yamamoto, Noboru; Kosaka, Kiyoshi; Shiga, Katsutoshi. Kawasaki Steel Giho. 1991, vol. 23, no. 2, p. 112–118.
2) Mada, Akiko; Maruta, Makoto. Kajima Gijutsu Kenkyuusho Nenpo. 2003, vol. 51, p. 63–68.
3) Building Standards Act. Article 79.
4) Architectural Institute of Japan. Standard for Structural Calculation of Steel Reinforced Concrete Structures. 2001.