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Super High HAZ Toughness Technology with Fine Microstructure Imparted by Fine Particles

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Abstract

In order to produce high HAZ toughness steel plates with tensile strength of 490MPa to 590MPa class, the innovative technology for HAZ microstructure refinement, HTUFF®, has been developed. Fine dispersion of oxides and/or sulfides in steel has been tried to retard γ grain growth in the HAZ near a weld fusion line. It has been discovered that very small oxides and/or sulfides with sizes of several 10nm to several 100nm can be dispersed in steel by the appropriate addition of Mg and/or Ca into steel. Utilizing these fine particles containing Mg or Ca, the strong pinning technology to retard γ grain growth in a HAZ has been commercially established. Based on the concept of HTUFF providing excellent HAZ toughness, high-performance structural steel plates have been mass-produced.

1. Introduction

Higher reliability, larger scale, and reduced weight are required of welded steel structures, lately, in view of social requirements such as enhanced safety, environmental protection and energy conservation, and also of severer resource development conditions. In such a situation, further enhancement of toughness and strength and increase in thickness have come to constitute important development subjects regarding heavy steel plate products having tensile strength of 490 to 590 MPa classes, which are widely used for welded steel structures. On the other hand, for the purpose of reducing the construction costs of a steel structure, high-efficiency welding methods applying high heat input have come to be widely employed. Against this background, there has been a strong need for the development of a heavy steel plate product that is excellent in the toughness of heat affected zones (HAZs) of a welded joint and that meets the requirements of high-heat-input welding, high-strength, large-thickness, and high-toughness.

As an example of conventional plate products having higher HAZ toughness, heavy plates of TiN steel, in which the pinning effect of TiN is utilized, have been widely applied[1]. Besides the above, intragranular transformation steel, in which various kinds of precipitates and oxides are used as the nuclei of ferrite transformation, has been developed[2,3]. Recently, however, such high levels of material strength and thickness, welding heat input and HAZ toughness have come to be required that there are cases where conventional steels fail to realize a sufficiently high HAZ toughness. For this reason, the establishment of a technology to realize a yet higher HAZ toughness has been in high need.

In view of the above situation, Nippon Steel Corporation has succeeded in developing a new HAZ toughness enhancement technology, which is called Super High HAZ Toughness Technology with

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Fine Microstructure Imparted by Fine Particles (HTUFF®, pronounced "eich-tuf"). In that technology, fine particles of thermally stable oxides and sulfides are dispersed in steel, and thus it is a technology that remarkably refines the structure of HAZ by utilizing new types of particles different from simple TiN[4-7]. Heavy steel plates produced by the HTUFF are a new type of high-performance heavy steel plates excellent in HAZ toughness satisfying the requirements of high-heat-input welding, high-strength, large-thickness, and high-toughness[8-13].

This paper outlines HTUFF focusing on the measures to cope with high-heat-input welding, and then describes the effectiveness of this technology in welded joints of commercially manufactured plates steels that have been developed on the basis of HTUFF for applications in the fields of building construction, shipbuilding, offshore structures and line pipes are also introduced in this special issue.

2. Improvement of HAZ Toughness

2.1 Dominant factors of HAZ toughness of high-heat-input welding

In the HAZ of 490 and 590 MPa classes steel near a fusion line of high-heat-input welding, austenite (γ) grains grow significantly owing to heating to a temperature of 1,400°C or higher for a considerable time period, and in addition, as a result of a low cooling rate in the transformation temperature zone, the HAZ microstructure becomes coarse, and its toughness is lowered as a consequence. In many cases, coarse grain boundary ferrite (GBF) and/or ferrite side plates (FSPs) form at boundaries of the coarse γ grains, and the lower the cooling rate, the more significant the growth of the GBF and FSPs becomes. In the case of high-heat-input welding of 490 to 590 MPa classes steel, it is difficult to prevent the formation of such a coarse microstructure as described above.

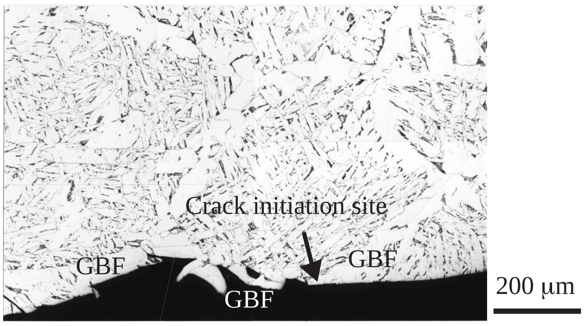


Fig. 1 Microstructure near crack initiation site in HAZ near weld fusion line of electrogas arc welding joint of 490MPa class steel

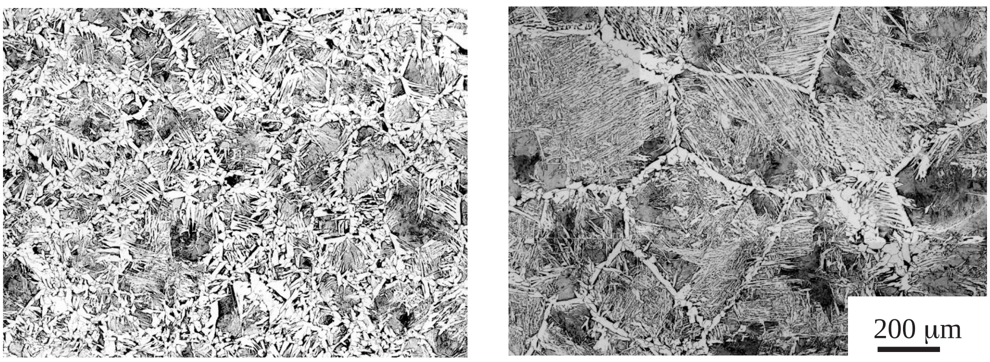
Fig. 1 shows a microstructure near the initiation site of a brittle fracture that occurred to a HAZ near a fusion line of an electrogas arc welding joint of a 490 MPa class steel. A coarse GBF grain several hundred micrometers in length acted as the initiation site and the propagation route of the fracture. This is presumably because, in addition to the coarsening of the GBF owing to the high-heat-input of welding, impact strain concentrated to the GBF, which is a soft structure, to cause the fracture[14]. It has been confirmed that, in the case where coarse FSPs form, there is also a similar effect detrimental to toughness.

From the above, the coarse structures forming at the γ grain boundaries constitute a significant dominant factor of the toughness of a HAZ in high-heat-input welding.

2.2 Effects of γ grain size on HAZ toughness of high-heat-input welding

It is considered that the morphology of the coarse GBF and FSP grains is influenced by the distribution of γ grain boundaries, which are their transformation sites, in other words, the morphology is influenced by the size of γ grains[15]. On this assumption, the authors prepared three kinds of specimens having different morphologies of GBF and FSP grains by controlling the size of γ grains to three size ranges, and examined the toughness of the specimens. Herein described are the examination results of HAZ specimens of a 490 MPa class steel simulating submerged arc welding (SAW) with a heat input of 10 kJ/mm and electroslag welding (ESW) with a heat input of 70 kJ/mm. **Fig. 2** shows the microstructures of two HAZ specimens simulating the condition of SAW, one having a γ grain size of 100 μm, and the other 400 μm, approximately. The size of local coarse structures was evaluated by measuring the lengths of five largest GBF or FSP grains in a field of view 3.6 mm^2 in area at a section surface of simulated HAZ microstructure.

Fig. 3 shows the size of coarse structures in the simulated HAZs and the influence of γ grain size over the toughness of the HAZs. In the figure it is seen that as the γ grain size decreases, the length of the GBF or FSP grains become shorter, and at the same time, toughness increases. It should be noted, however, that in the case of the HAZ specimens simulating ESW, even when the γ grain size decreases from 400 to 250 μm, approximately, the length of the GBF or FSP grains does not decrease significantly, and as a result, toughness does not necessarily increase. Therefore, in order to enhance the toughness of a HAZ, it is necessary to make γ grains fine to the extent that



(a) γ grain size : approx. 100 μm (b) γ grain size : approx. 400 μm

Fig. 2 Simulated HAZ microstructure of 490MPa class steel corresponding to SAW with 10kJ/mm

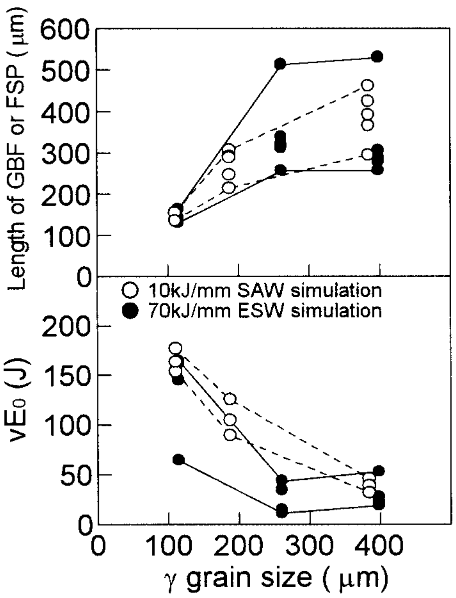


Fig. 3 Influence of γ grain size on toughness and coarse microstructure size in simulated HAZ of 490MPa class steel corresponding to high heat input welding

the GBF and FSP grains become substantially fine.

From the above, it was concluded that refining the transformation structures forming at γ grain boundaries by refining the γ grains is effective for enhancing the toughness of a HAZ in high-heat-input welding.

2.3 Control of HAZ microstructure

The concept of HAZ microstructure control through HTUFF is schematically illustrated in **Fig. 4**. The figure shows the distribution of γ grains in a HAZ during heating and the transformation structure that forms in one of the γ grains after cooling. In the case of TiN steel, which is shown in Fig. 4(a), it is difficult to retard the growth of γ grains near a fusion line, and coarse GBF and FSP grains form at boundaries of coarse γ grains. In the case of intragranular transformation steel, which is shown in Fig. 4(b), intragranular ferrite (IGF) forms inside γ grains, and as a result, the growth of transformation structure at γ grain boundaries is retarded. In contrast to these conventional technologies, in the case of steel according to HTUFF, which is shown in Fig. 4(c), the growth of γ grains near a fusion line is strongly retorted, the γ grains are kept as small as possible, and thanks to this effect, the microstructures forming at the γ grain boundaries are finer. This is the basic concept of HTUFF.

3. Development of HAZ Microstructure Refinement Technology, HTUFF

3.1 Retardation of γ grain growth

The pinning effect in crystal grain growth is expressed by Zener's equation (1)[16-18].

$$R = (4/3) \cdot (r/f) \qquad (1)$$

where, R is the radius of a crystal grain, r is the radius of a second phase particle, and f is the volume fraction of second phase particles. According to equation (1), it is basically necessary for retarding the growth of crystal grains to minimize the value of r/f. Since the subject of HTUFF is a HAZ near a fusion line, the distribution of second phase particles at a temperature as high as 1,400°C is of importance. The most part of TiN, which is widely used in conventional steels, becomes solute when kept at such a high temperature for a long period, leading to a decrease in the value of f, and the outstanding particles of TiN not dissolved grow, leading to an increase in the value of r. As a result, the value of r/f increases and the pinning force is reduced.

The concept of strengthening the pinning effect envisaged in HTUFF is, in the first place, to use thermally stable second phase particles that do not easily dissolve or grow at a temperature as high as 1,400°C as pinning particles, and in the second place, to disperse such second phase particles homogeneously and finely in steel. The principal challenge in the development of HTUFF was to decrease the value of r/f, which represented the distribution of second phase particles at high temperatures, following the above reasoning. However, it has to be noted here that the increase in coarse second phase particles that may serve as the initiation site of a fracture must be avoided.

3.2 Creation of new pinning particles

In the development of HTUFF, the authors turned their attention to oxides and sulfides as the thermally stable second phase particles, took up Mg and Ca, which have strong affinity with O and S, and aimed at distributing their oxides and sulfides as fine particles in steel by adequately adding these metal elements to steel. As a result, they succeeded in homogeneously and finely dispersing the new types of pinning particles as shown in **Fig. 5** in steel. In this process, the contents of O and S in HTUFF steels are the same as in conventional steels, and nevertheless, coarse oxide and sulfide particles that may act as the initiation site of a fracture do not increase.

The pinning particles used in HTUFF steels shown in Fig. 5 are those of oxides and sulfides containing Mg and/or Ca, several tens to several hundreds of nanometers in size. Judging from the fact that these fine particles were found in steel that was water quenched from 1,400°C, they were not in solid solution but maintained their par-

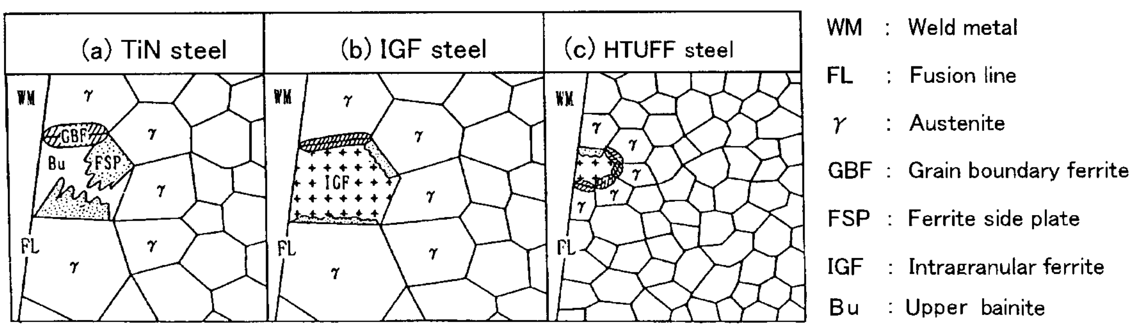


Fig. 4 Concept of HAZ microstructure control through HTUFF

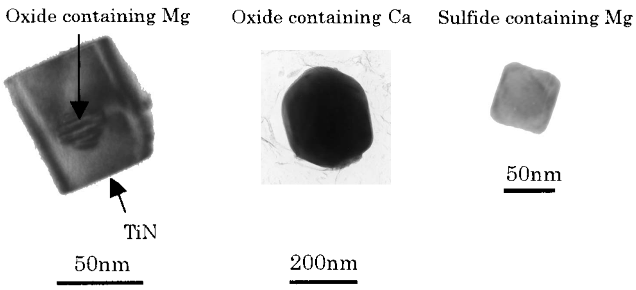


Fig. 5 Examples of pinning particles in HTUFF steel

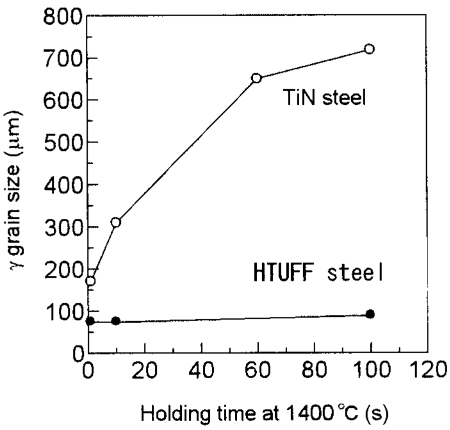


Fig. 6 Comparison of γ grain growth behavior between HTUFF steel and TiN steel simulating HAZ near weld fusion line

ticulate form at a temperature of 1,400°C. Whereas the oxide and sulfide particles used in conventional steels are several micrometers in size, the size of the new pinning particles of HTUFF is as small as 1/100 to 1/10, approximately, that of pinning particles conventionally used, and HTUFF is characterized by having these fine pinning particles densely dispersed in steel. This means that the value of r/f, which represents the distribution of oxide and sulfide particles at high temperatures, is far smaller in steel according to HTUFF than in conventional steels. **Fig. 6** shows an example of comparison of γ grain growth behavior between an HTUFF steel and TiN steel. It is seen in the figure that γ grains of the HTUFF steel little grow even when they are kept at 1,400°C for 1 to 100s, a condition simulating a HAZ near a welding fusion line; thus, a very strong pinning effect not achieved with conventional steels is realized through HTUFF.

3.3 Effect of HTUFF in welded joints of commercially manufactured plates

Next, the effect of HTUFF in welded joints of commercially manufactured plates is explained on an example of a developed 590 MPa class steel for building construction. **Table 1** shows the chemical composition and the thicknesses of plates of the developed steel. Mg and Ca were added to the steel adequately during its production for the purpose of intensifying the pinning effect in a HAZ. The developed steel was welded under the conditions specified in **Table 2** to form welded joints simulating the joints of a diaphragm of a box column. Plates of conventional TiN steel were also welded under the same conditions for comparison purposes. The HAZ microstructures of the ESW joints of the developed and conventional steels are compared in **Fig. 7**. The HAZ microstructure of the developed steel near a fusion line is much finer than that of the conventional steel. The above result definitely confirms the effect of HTUFF to refine γ grains of a HAZ of a welded joint of commercially manufactured plates with an extremely high-heat-input welding.

4. Closing

In view of requirements for high-heat-input welding, high-strength, large-thickness, and high-toughness of 490 to 590 MPa class heavy steel plate products, a new technology to obtain a fine-structured and high-toughness HAZ called HTUFF was developed for the purpose of realizing excellent toughness in a HAZ of a welded joint. This is a technology whereby thermally stable oxides and sulfides containing Mg and/or Ca are dispersed in steel as fine particles, the growth of γ grains in a HAZ near the fusion line of a welded joint is strongly retarded by the fine particles, and as a result of the unprecedentedly strong γ grain refining effect of the particles, the HAZ microstructure is made fine. Heavy plate products according to the developed technology have been used for widely varied fields of application such as building construction, shipbuilding, offshore structures and line pipes, and the total shipment of such products has surpassed 280,000 t. The technology is expected to find still wider applications.

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Table 1 Chemical composition and thickness of developed 590MPa steel plates for box columns

Chemical composition (mass %)									Thickness
C	Si	Mn	P	S	Others	HTUFF	Ceq	Pcm	(mm)
0.10	0.16	1.56	0.006	0.002	Cu, Ni, Nb,V, Ti	Treated	0.39	0.23	60, 80

Ceq=C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14
Pcm =C+Si/30+ (Mn+Cu+Cr) /20+Ni/60+Mo/15+V/10+5B

Table 2 Welding condition of developed 590MPa steel plates for box columns

Welding method	Welding pass	Welding heat input	Joint geometry	Skin plate	Diaphragm
ESW	Single pass	87kJ/mm	T joint	80mm	60mm

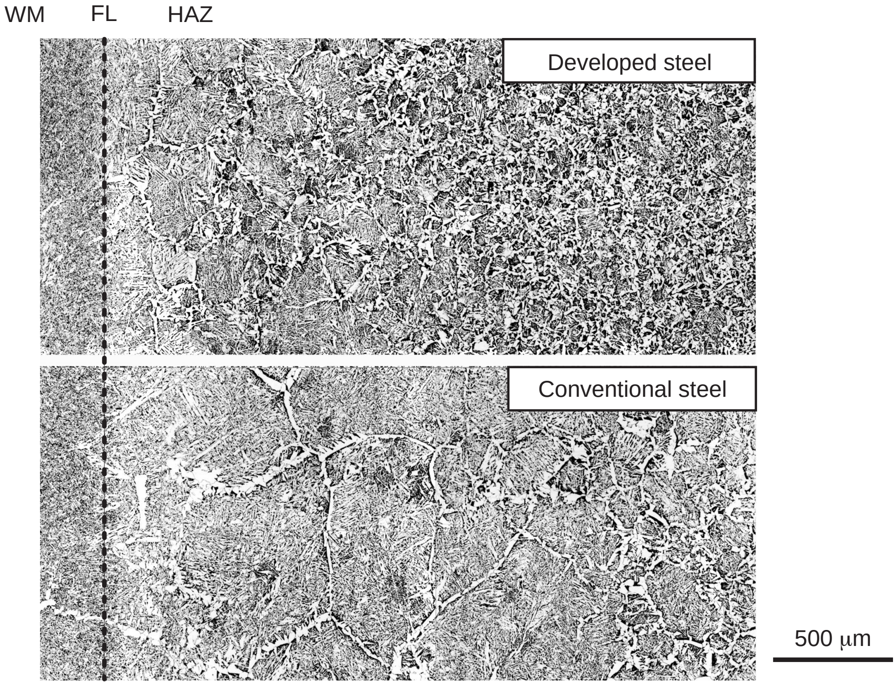

Fig. 7 Comparison of HAZ microstructure in ESW joints between developed steel and conventional TiN steel

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