

Flash-Butt Welding of High Strength Steels

Yasutomo ICHIJAMA*¹Shinji KODAMA*¹

Abstract

Welding technologies with high productivity is very attractive in the field of welding. Flash welding is essentially very fast welding and can meet this requirement. However, their weld properties, especially fracture toughness, have not been acceptable and thus the application has been limited. In this study, factors governing flash weld qualities have been studied using high strength steels. The effects of welding conditions and base metal chemical compositions on the weld defects are summarized. The effects of inclusions and microstructures on weld toughness are also discussed. Through these results, quality improvement methods by applying special upsetting conditions have been observed and these are presented in this paper.

1. Introduction

Unlike arc welding that is 'line welding' in which the welding point moves along a prescribed line, flash butt welding is 'plane welding' in which the opposed planes are welded at a stroke. Therefore, this welding method is extremely efficient¹⁾. It is applied to weld wheel rims in the automotive industry and joint hot-rolled coils in the steelmaking industry. Thus, it is applied largely to thin sheets^{2,3)}. The major welding quality problem in those applications is weld cracking of the sheet being formed, and reducing defects in welded interfaces is called for. In terms of the application of flash butt welding to plates, on-site welding of line pipes, welding of rails, welding of marine structures and vessel mooring chains, etc. can be cited.

Taking on-site welding of line pipes, for example, the flash butt welding method requires only about 3 minutes to weld two pipes 750 mm in diameter and 19 mm in wall thickness, whereas the ordinary automatic arc welding process takes 90 to 120 minutes to do the same⁴⁾. In flash butt welding of plates, securing the required weld toughness, as well as restraining weld defects, is called for. Studies carried out in the past mostly dealt with weld defects: there are very few analytical studies on weld toughness. Generally speaking, the weld toughness deteriorates much faster than the base metal toughness^{5,6)}, hence improving the weld toughness is necessary.

In recent years, more and more steel products having higher

strength are used in every sector of industry. With the continual increase in strength of steel products, it has become increasingly difficult to secure the required weld quality. Under such conditions, a study was conducted on the factors that influence the quality of flash butt welds for high strength steels and means of improving the quality of welds. This paper describes the study results.

2. Factors That Cause Defects in Flash Butt Welds of High Strength Steel

Defects which can occur in flash butt welding are similar in form to defects observed in welds of electric welded tube (penetrator, cold weld) or those observed in gas pressure welded joints (flat spot). Dispersed oxide lies beneath the fractured surface. An example of this is shown in **Photo 1**. The photo reveals a shallow micro-dimple, and microscopic nonmetallic inclusions (hereinafter simply referred to as "inclusions") can be observed in the bottom of the dimple. These are oxides containing Si, Mn and Al which were formed in the sheet edge in the flashing process and remained in the weld surface without being ejected in the upset force application process. The principle of heating in flash butt welding is chiefly the generation of a flash. The process involved is repetitions of three phenomena: (1) contact between convex edges, (2) resistance heating and melting, and (3) breaking of contact edges by electromagnetic pinching force and spattering of contact edges by subsequent arc discharge. If an excessively large flash occurs before upsetting, a considerably larger

*¹ Steel Research Laboratories

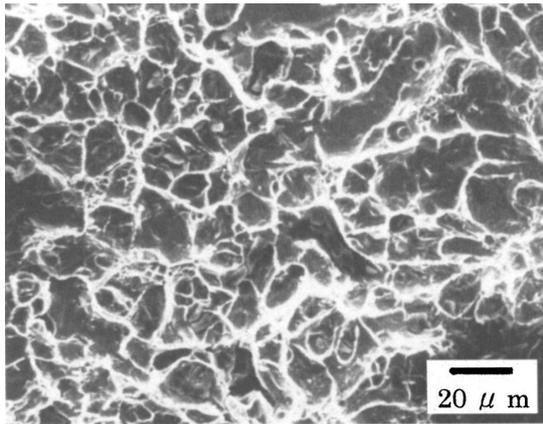


Photo 1 SEM image of fractured surface in defect area

crater is formed at the sheet edge. This crater can cause a weld defect.

Fig. 1 shows an example of the influence of welding conditions (Steel A in Table 1). The weld surface defect is evaluated in terms of the rate that cracking occurs in a bending test. The rate is obtained as the ratio of the total sum (Σl) of crack lengths (l) to the overall width of the test piece used in the bending test (= number of times the test piece is bent (n) × test piece width (L)). It can be seen that increasing the upset length and applying preheating before the flashing process are effective means of reducing weld cracking. As shown in

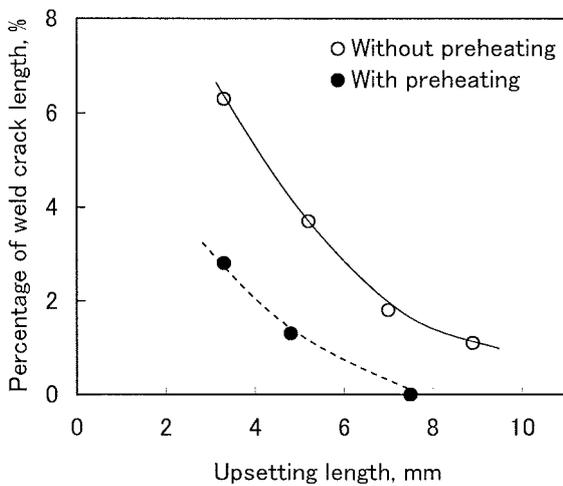
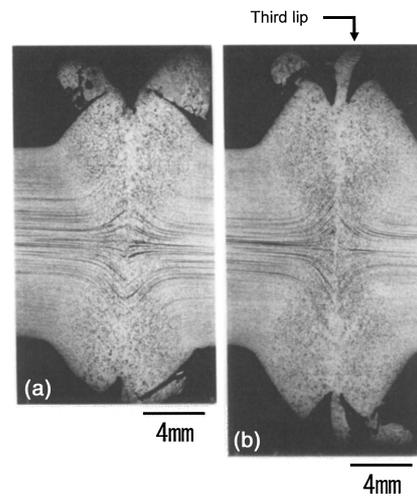


Fig. 1 Effect of preheating and upsetting length on weld crack length (Steel A)

Photo 2, under welding conditions that include the application of preheating, small burrs occur in the weld interface. Thus, the formation of a so-called third lip⁷⁾ becomes conspicuous. The third lip is formed when a molten layer which has been formed on the test piece edge is removed by the upsetting force. It is considered, therefore, that the reason why the weld defect can be reduced by the application of preheating is that the increase in heat input promotes the formation of a molten layer, making it easier to expel the unwanted oxides by the application of an upset force⁸⁾.

In principle, the steel's chemical composition largely determines the rate of occurrence of weld surface defects. In the case of mild steel sheets, the rate of occurrence of cracking generally increases as the Al content of the steel is increased. This is because mild steel contains less Si and Mn than high-strength steel and its susceptibility to cracking is determined largely by the readily oxidized Al⁹⁾. On the other hand, some grades of high-strength steel are subject to marked cracking. This suggests that not only the contents of oxidizing elements, but also the ductility of the weld, are related to crack susceptibility. A study was conducted on those effects using steel sheets 2.4 mm to 3.2 mm in thickness and 323 MPa to 691 MPa in tensile strength (see Table 1, Gr. D). The test specimens used were Si-Mn-based mild steel sheets and high-strength steel sheets, including sheets containing some amounts of Cr, Nb and V. They were subjected to a bending test, with the punch diameter and bending angle being 7 mm and 180°, respectively, and the weld defects were evaluated in terms of the rate that cracking occurred. Fig. 2 shows the influences of C and Si contents on weld crack length, with Si content at three different levels. Both C and Si increase the weld



(a) Without preheating (b) With preheating

Photo 2 Cross-section of welds

Table 1 Chemical compositions of steels used (mass%)

Mark	Steel	C	Si	Mn	P	S	Cr	Ni	Mo	Nb	Al	Others	Thickness (mm)
A	X80	0.082	0.25	1.84	0.011	0.001	-	0.19	0.09	0.043	0.023	Cu, Ti, V	12
B	980HT	0.07	0.23	1.9	0.015	0.008	1.8	-	-	-	0.04	Ti, V	13
C	X65	0.087	0.19	1.29	0.011	0.0007	-	-	0.22	0.034	0.033	Ca	8
* Quenching: 920 × 15 min + WQ, Tempering: 600 × 15 min + AC													
Gr. D	Sheet steels	0.013-0.171	0.01-1.24	0.19-1.62	0.009-0.026	0.009-0.023	0.0-0.4	-	-	0.0-0.05	0.002-0.100	V	2.4-3.2

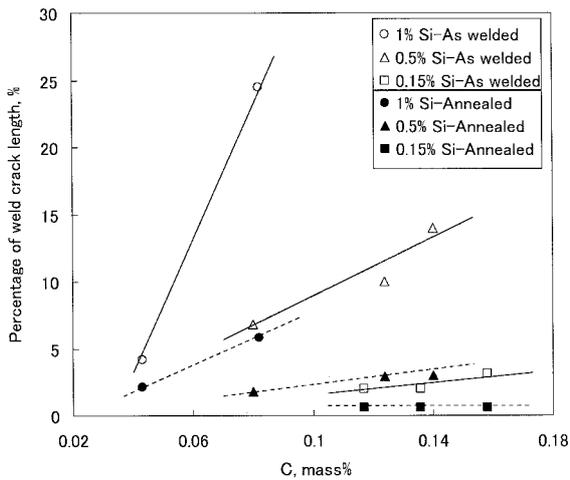


Fig. 2 Effect of C and Si contents on weld crack length (Steel Gr. D)

crack length. When welded joints are softened by annealing (heating at 950 °C for 30 min + cooling in a furnace) after welding, the rate of cracking decreases markedly.

Fig. 2 indicates that the influence of Si content is exponential and that both C and Si increase weld susceptibility to cracking. Therefore, a crack susceptibility evaluation expression (Feq) was formulated, including Mn and Al, as shown in Equation (1) to regressively obtain the values of coefficients a , b , c and n using 40 different grades of high strength steels as specimens.

$$Feq = (C - a) \{Si^b + 1 \cdot Mn^n + (c \cdot Al)^n\} \quad (1)$$

(C, Si, Mn, Al: mass%)

As a result, $a = 0.03$, $b = 0.1$, $c = 3$ and $n = 2$ were obtained. The measured and calculated effects of the steel's chemical composition on crack susceptibility are shown in Fig. 3. It can be seen that there is good correlation between them. Qualitatively, Si,

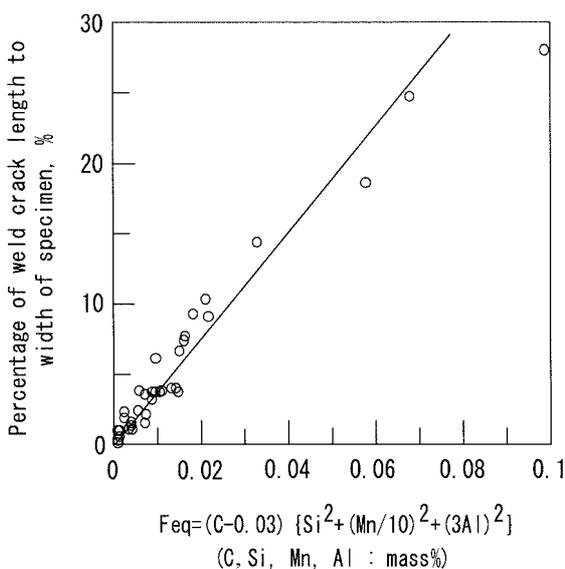


Fig. 3 Effect of base metal chemical compositions on weld crack length (Steel Gr. D)

Mn and Al affect as the formation of oxides in the steel, while C determines steel ductility. It is considered, therefore, that these are the cause of cracks originating in those oxides spreading to the surrounding parts⁹⁾.

3. Factors Influencing Toughness of Flash Butt Weld of High Strength Steel

Generally speaking, the toughness of the heat-affected zone (HAZ) of high-strength steel is largely determined by the welding heat input and the steel's chemical composition. However, in the case of flash butt welding, which is a kind of pressure welding, the weld toughness is influenced by many factors which are difficult to interpret. A systematic study was undertaken for those factors using Steel A shown in Table 1.

Fig. 4 shows the results of a Charpy impact test on the welds. The toughness of as-welded joints is extremely poor. It improves markedly when the joints are subjected to a normalizing heat treatment (920 °C for 5 min + air cooling) after welding. Although increasing the upset length was found to be effective in reducing weld defects, it tends to adversely affect the weld toughness as it causes $vTrs$ to increase. As shown in Photo 3, the microstructure of the weld is a coarse upper bainite similar to the structure observed in HAZ in ordinary arc welding using a large heat input. A locally softened zone was observed at the weld interface. If this is overly wide, however, it can cause the weld toughness to deteriorate¹⁰⁾. The problem of such uneven hardness can be solved by applying normalizing heat treatment after welding.

The notch position stepwise was changed by increasing the distance from the weld interface in increments of 1 mm and studied the relationship between the prior austenite grain size and $vTrs$ at each notch position. The study results are shown in Fig. 5. For the purpose of comparison, we carried out a synthetic HAZ test simulating the flash butt welding thermal history, obtained synthetic HAZ specimens by varying the maximum attainable temperature from 900

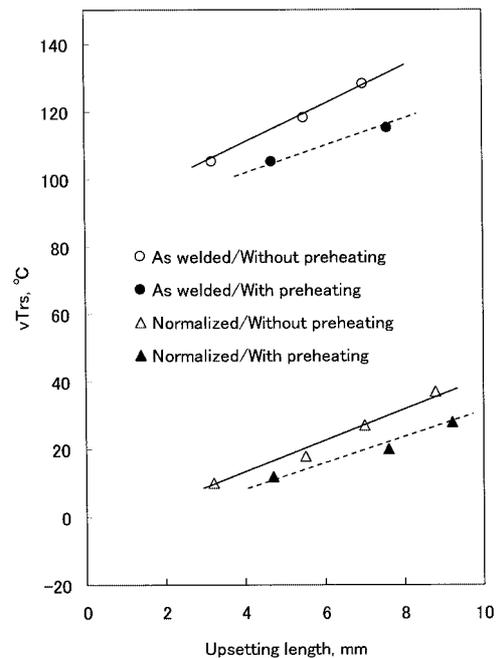


Fig. 4 Effect of upsetting conditions on $vTrs$ (SteelA)

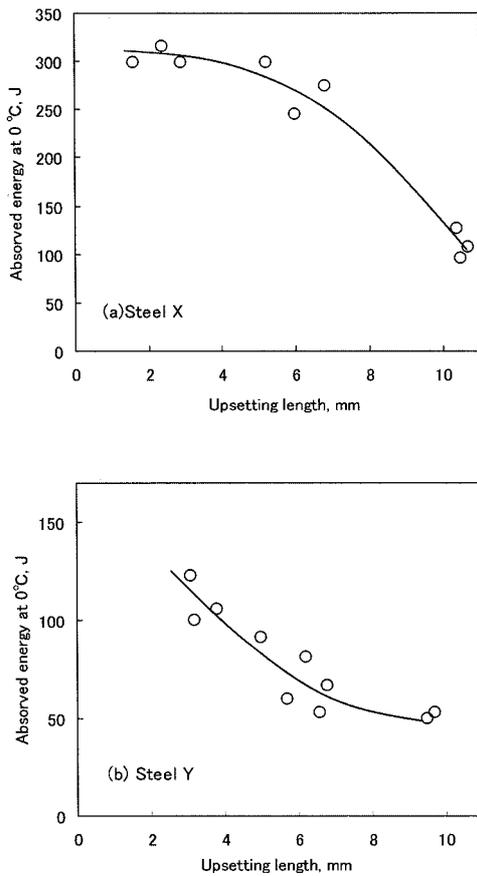


Fig. 7 Effect of upsetting length on absorbed energies using forge-upset simulation

pressure application and plastic flow, inclusions in the steel also cause the weld toughness to decrease. Therefore, in order to enhance the toughness of the weld, it is necessary to eliminate the unfavorable factors relating to inclusions and improve the steel structure.

4. Improvement of Weld Quality by Upset Control for Melting and Oxide Removal

In Section 2, a discussion is provided on how applying a preheating process in flash butt welding promotes the formation of a fusion zone and is an effective means of reducing welding defects. Thus, applying a preheating process is considered to be one means of removing unwanted inclusions from the weld interface. However, since any preheating process is followed by the flashing process, it is difficult to form on a stable basis a fusion zone that is effective for expelling oxides. With the upsetting process, by contrast, it is possible to Joule-heat the entire weld surface evenly and to control the Joule heating with good repeatability by varying the electric current value and duration. Since it is the final process in flash butt welding, it directly influences the final weld quality. Therefore, from the standpoint of positively forming a molten metal and expelling oxides in the upset process, a technique was studied to improve the weld quality through removal of welding defects and inclusions in steel, and experimentally found upset conditions suitable for that purpose.

In the experiment, a round bar (78 mm in diameter) of high-strength Steel B (980 MPa) shown in Table 1 was used. Test pieces

(butt face: 13 mm × 13 mm, length: 120 mm) were cut out from the bar along the center axis and subjected to welding. In order to improve the structure-related factors that influence the weld toughness, the welded test pieces were subjected to one of three types of heat treatment—solution treatment at 1,200 °C for 1 hour + water cooling, solution treatment at 900 °C for 1 hour + water cooling and solution treatment at 900 °C for 1 hour + oil cooling.

Fig. 8 shows the change in upset displacement with the lapse of time when the upsetting current density (I_u) was gradually increased. Fig. 8 (a) shows the change in displacement under ordinary upset conditions (Condition A). Following a mild change in displacement in the flashing process (A-B in the figure), the upsetting process starts at Point B. Right after the upsetting process starts, the upsetting displacement sharply increases by about 0.5 to 1.0 mm as indicated by the curve between Points B and C. This displacement, called the initial upsetting displacement⁹⁾, is observed when those parts which have small reaction force, such as the fusion zone and gaps between members formed in the flashing process, are pressure-welded. With the increase in upsetting current density, the gradient of the displacement curve increases gradually (Condition B). When the upsetting current density is increased to 150 A/mm², a sharp increase in displacement, like the one observed between Points B and C in the early stage of upsetting, also occurs between Points D and E and between Points F and G (Condition C). It was confirmed by high-

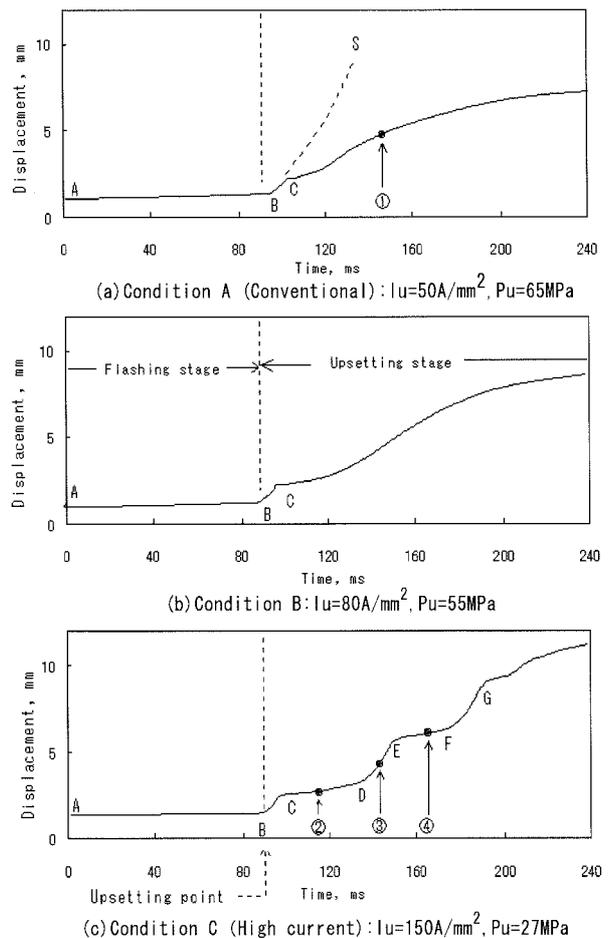
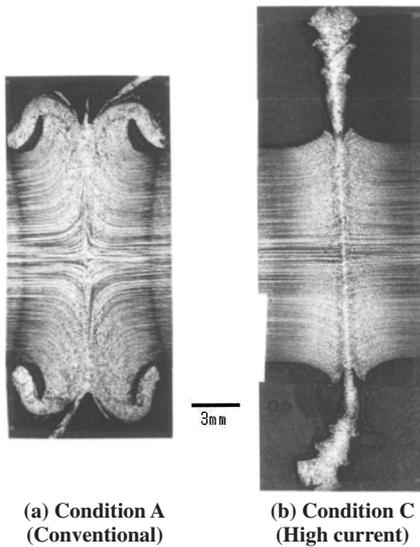


Fig. 8 Changes in upsetting displacement with upsetting current density

speed video photography that the above characteristic dynamics correspond to repetitions of formation and extruding of a molten layer from the weld interface.

Photo 4 compares weld cross-sections obtained under Conditions A and C. Under Condition C (large current), a considerably large fin (thin burr) extruded from the weld interface can be observed. This fin is far longer than the ordinary third lip. It was formed when molten metal that had been extruded from the entire weld surface fused by a large upsetting current cooled down. As shown in **Fig. 9**, the absorbed energy under this condition is much larger than that under conventional conditions.

The authors studied the influence of increasing the upsetting current on the embrittlement of the weld due to inclusions in the steel using the simulative test method shown in **Fig. 6**. At a large upsetting current, even Steel Y containing relatively large amounts of inclusions showed excellent weld toughness, with the absorbed



(a) Condition A (Conventional) (b) Condition C (High current)

Photo 4 Cross-section of welds (Steel B)

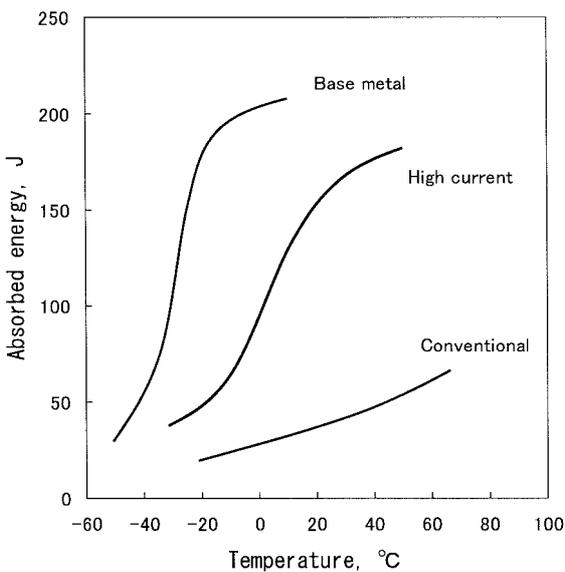


Fig. 9 Charpy test result (Steel B)

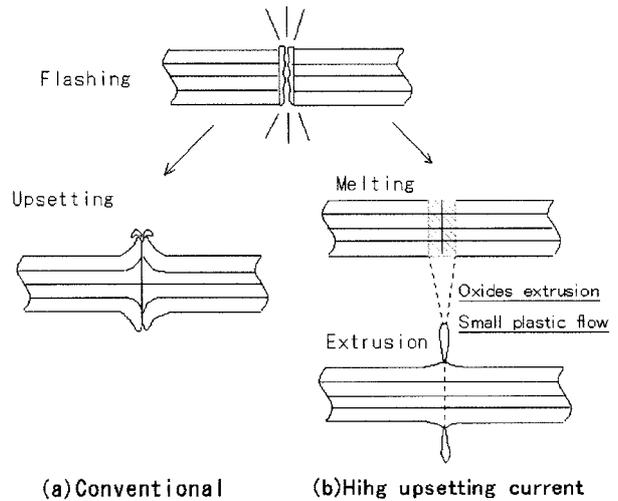


Fig. 10 Schematic illustrations showing the effect of upsetting current

energy being 150 J at 0 °C when the upset length was 10 mm. The reason for this is considered to be that in the upsetting process, the inclusions were separated from the base phase and forced out of the system together with the molten layer.

From the above study results, it was considered that the weld showed good toughness at a large upsetting current as the formation and extrusion of a molten layer took place in the upsetting process, removing not only the oxides formed in the flashing process but also inclusions in the steel - the two factors that adversely affect weld toughness. **Fig. 10** shows the mechanism by which the weld toughness improves¹⁾.

5. Improvement of Toughness of As-welded Steel by Application of Upsetting Current using a Stored-energy Type Power Supply

The upset control described above eliminates the inclusions-related factors that adversely affect weld toughness by fusing and extruding the weld surface. To improve the structure of the weld, suitable post-welding heat treatment is applied. In order to improve the weld quality without any heat treatment, it is necessary to substantially improve the structure of the weld. One possible way of achieving that is to lower the welding heat input as much as possible and thereby create a finer weld microstructure. In the field of fusion welding, a high-intensity heat source is employed to lower the welding heat input, as in electron-beam welding and laser welding. There are many reports on practical applications of this method. In resistance pressure welding too, if the welding current density can be increased to allow for rapid welding, it becomes possible to omit the preheating and flashing processes and implement welding with small heat input using the upsetting process alone. The authors studied an upset welding technique using a homo-polar generator (HPG) capable of outputting extreme electrical currents in the range 100 to 500 kA, and discussed the improvement in weld quality without any heat treatment by the use of a small welding heat input and upsetting displacement. The study results are described below.

The operating principle of the HPG is based on the Faraday disk as shown in **Fig. 11**. It stores kinetic energy by turning a rotor in a magnetic field and discharges the stored kinetic energy in the form of electrical energy. Because of its operating principle, the HPG is

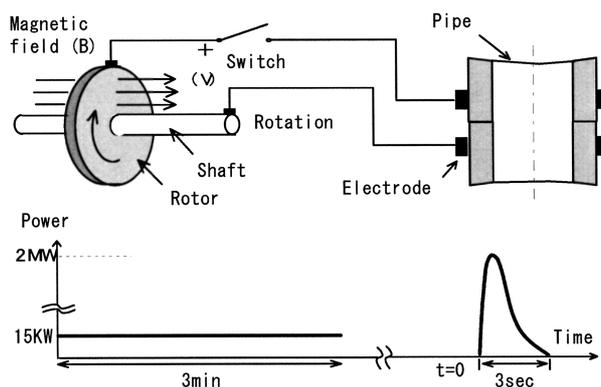


Fig. 11 Process schematics of upset welding using HPG

capable of producing massive currents. Voltages are generated between the rotor shaft and disk as the rotor turns in the magnetic field. Current is discharged when the welding circuit is switched on. The current discharged is supplied to the material to be welded via the electrode. The junction is rapidly heated by Joule heat and subjected to upset welding when it reaches the prescribed temperature^{11,12)}.

Photo 5 shows the microstructure of a weld of X65 seamless steel pipe 89 mm in outer diameter and 8 mm in wall thickness (Table 1, Steel C of QT type) obtained by using a peak welding current of 250 kA. The weld interface reveals a fine ferrite structure, the grain size of which is 4 to 6 μm - almost the same as that of the base metal. The marked growth of grains, the formation of upper bainite, etc. that are common with flash-welded junctions are not seen. Flash welding steel material of this size normally requires 30 seconds or so. With HPG, it takes only approximately 3 seconds. This reduction in welding time contributes to the refinement of the weld microstructure. The grains are somewhat elongated in the plate thickness direction. This is considered to be due to the influence of plastic flow during upsetting.

Fig. 12 shows the Charpy test results of welds obtained using HPG. The absorbed energy at the weld interface at 0 °C is 70 J (7.5 mm sub-sized specimens), nearly the same as the toughness of a flash-welded joint subjected to heat treatment after the welding. The highly absorbed energy mentioned above is attributable to the refinement of the weld structure by the use of a small heat input and upsetting displacement. This is considered to suggest that welding with HPG may be effective as a means of improving the weld quality

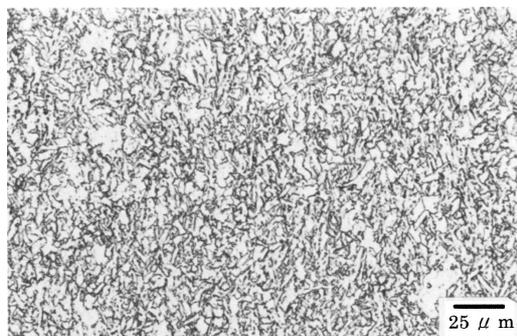


Photo 5 Optical micrograph of microstructure (Steel C)

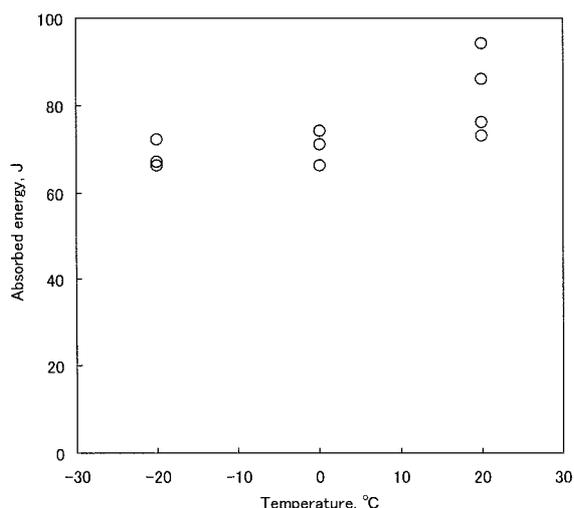


Fig. 12 Charpy test results of homopolar weld (Steel C, 7.5mm sub-sized specimens)

without applying any heat treatment. The problem that remains to be solved is the formation of a crystalline texture in the weld junction mentioned in Section 3. Solving this problem requires study of the influence of the steel's chemical composition too. This is therefore a future task to be tackled.

6. Conclusion

Thus far, the authors analyzed welding defects and weld toughness - important elements in the quality of flash-welded joints of high-strength steel - and discussed various factors that influence those quality elements. On the basis of the analysis results, a new welding technique was attained which helps improve the weld quality, and described the mechanism that improves the weld toughness. Although flash welding is a simple and efficient welding technique, it has limited applications because of the difficulties involved in ensuring the required weld quality. It is considered that the two upset control methods described in this paper are perhaps the most rational approaches to the problems relating to inclusions and the microstructure of welds, and that these are promising technologies for improving the weld quality. At present, the maximum cross-section area to which they can be applied is limited because of the limited power supply capacity, responsiveness to welding pressure, etc. In the future, however, they will become more practical with improvements in the accuracy of control and the development of new power supplies.

References

- 1) Ichiyama, Y.: IIW Doc. 2001, X II-1664-01, IIW
- 2) Ulmer, K.: Stahl and Eisen. 98 (26), 1400 (1978)
- 3) Dickinson, D.E.: Welding design and Fabrication. 47 (5), 64 (1979)
- 4) Turner, D.L.: Journal of Energy Resources Technology. 108, 347 (1986)
- 5) Suzuki, M., Endo, S.: J. JWS. 8 (2), 58 (1990)
- 6) Ichiyama, Y. et al.: 178th Workshop on Special Welding Process. Tokyo, 2002
- 7) Ando, K., Nakata, S.: J. JWS. 40 (2), 137 (1971)
- 8) Ichiyama, Y. et al.: J. JWS. 21 (2), 219 (2002)
- 9) Saito, T. et al.: J. JWS. 13 (3), 365 (1995)
- 10) Suzuki, S. et al.: Tetsu-to-Hagané. 73, 558 (1987)
- 11) Hudson, R.S.: ASME International. 319 (1986)
- 12) Ichiyama, Y.: 3rd International Pipeline Technology Conference. Brugge, 2000-5