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Effect of Electromagnetic Stirring on Weld Solidification Structure of Austenitic Stainless Steels†

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Abstract

Effect of electromagnetic stirring on refining of weld solidification structure was investigated for austenitic stainless steels of SUS 304, 316, 321 and 310S, 2 and 8 mm in thickness, with GTA bead-on-plate welding. The experimental scope in this investigation was less than 15 Hz in stirring frequency, less than 700G on weld surface in magnetic field, and welding conditions of GTAW were 200A-150 mm/min for 2 mm thick sheet and 200 to 300A-150 to 300 mm/min for 8 mm thick plate. As a result, there was an optimum in stirring frequency in 5 to 10 Hz and was better with increasing in magnetic force, in order to make fine grain in austenitic stainless steel. The mechanism of refining is also estimated to be the same as that of aluminum alloys, that is, dendrite fragmentation by fluid flow with stirring action.

KEY WORDS: (Electromagnetic Stirring) (Weld Solidification Structure) (Grain Refining) (Stainless Steel)

1. Introduction

The importance of fine equiaxed grains as opposed to columnar grains has long been also recognized in welding. There are various enhanced properties associated with a fine grain structure such as improved low-temperature mechanical properties, solidification crack susceptibility, corrosive resistance and formability and reduced segregation scale.

A number of techniques have been developed to produce fine grain structures during solidification. The most common methods in welding, however, are to add small amounts of grain refining agents, inoculants to the molten pool or to flow the molten fluid compulsively by electromagnetic stirring.

For the latter the authors have reported some papers concerning probability for making fine grain in aluminum alloy welds during GTAW[1,2]. In these papers it was cleared that a compulsive fluid flow can cause dendritic fragmentation by bringing hotter liquid to the root of the dendrite arms, and that the fragments, when carried away, can serve as growth sites for new grains.

The present experiments were conducted to investigate the possibility of making fine grains in weld metal of austenitic stainless steels, 2 and 8 mm in thickness, with GTA bead-on-plate welding.

2. Experimental Procedure

2.1 Materials used

The materials used in this experiment are commercially used austenitic stainless steels, SUS 304, 310S, 321 and 316, of 2 and 8 mm in thickness, and chemical compositions of which are collectively listed in **Table 1**. The specimen size for each test are 80 × 150 × 2 mmt or 170 × 180 × 8 mmt.

2.2 Electromagnetic stirring apparatus

The principle of electromagnetic stirring have been reported previously[1,2]. The schematic illustration of the arrangement of magnetic coils, welding torch and specimen is shown in **Fig. 1**. The apparatus has two magnetic coils which are set above and below the specimen. The upper magnetic coil which is set at outer side of the gas nozzle tip is mainly used in this experiment, and the lower coil is additionally used when the strong magnetic field is required in 8 mm thick plate.

The upper coil is made by winding of 1000 turns of 0.8 mm diam copper wire on a water-cooled brass pipe and the lower coil is also 1000 turns on 32 mm diam iron core. **Figure 2** shows examples of the radial distribution of magnetic field on specimen surface which is made by the upper coil under a constant distance between the coil and the specimen. The intensity in magnetic field in this experiment is designated at the center axis of coil and on the specimen surface. Magnetic current is supplied by rectangle alternative current, up to 10A, of 0.1 to 100 Hz. The effect of increase in frequency on the fluctuation of the intensity in magnetic field was negligible.

2.3 Welding conditions

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Table 1 Chemical compositions of materials used.

Material	Thickness (mm)	Chemical composition (wt%)								
		C	Si	Mn	P	S	Ni	Cr	Mo	Ti
SUS304	2	0.08	0.55	1.11	0.027	<0.005	8.40	17.97	—	—
SUS304	8	0.049	0.56	1.00	0.031	0.004	9.27	18.20	—	—
SUS310S	2	0.09	0.71	1.65	0.016	<0.005	19.30	24.81	—	—
SUS310S	8	0.052	0.54	1.02	0.021	0.003	19.25	24.60	—	—
SUS321	2	0.09	0.72	1.08	0.024	<0.005	9.21	17.04	—	0.38
SUS321	8	0.07	0.69	1.02	0.027	0.003	9.27	17.08	—	0.42
SUS316	2	0.08	0.47	0.94	0.027	0.008	11.08	16.99	1.89	—

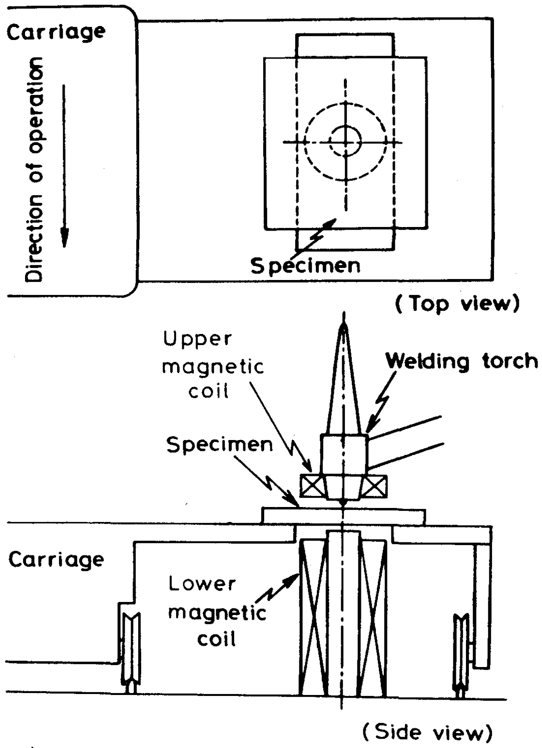


Fig. 1 Arrangement of magnetic coils, welding torch and specimen.

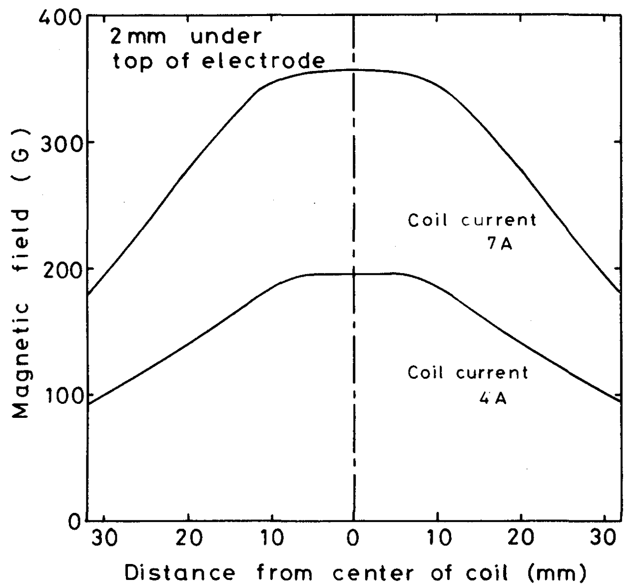


Fig. 2 Horizontal distribution of intensity in magnetic field.

Bead-on-plate welding is done with DCSP-GTAW without filler using an Analogue Transister Power Supply (800A, 45V).

The electrode is W-Th O_2 (2%) of 4.8mm diam and the distance between tip of the electrode and the specimen is constant at 2 mm in pure argon shielding of 20 l/min gas flow. Specimens are degreased with acetone prior to welding. Welding conditions used are 200A – 150mm/min for 2 mm thick sheets, and 300A – 150 mm/min and 200A – 300 mm/min for 8 mm thick plates.

2.4 Metallurgical investigation of solidification structure

In order to investigate the probability of the fine grained structure the weld is cut crosssectionally and longitudinally and the structure is investigated under an optical microscope X 25 to X 100 magnification after polished and etched by aqua regia (51%HCl–17%HNO_3 – 32%H_2O).

3. Experimental Results

3.1 Results for 2 mm thin sheet

3.1.1 Weld bead appearance

There are some limitations for the electromagnetic stirring conditions of thin sheet during welding, as excess fluid flow makes a burn through bead. Therefore the effect of electromagnetic stirring condition on the formation limit of burn through bead is investigated under same welding condition. **Figure 3** shows the formation limit for burn through bead for various stainless steels of 2 mm thick sheet. White mark shows sound bead and black shows burn through bead. The limit of magnetic field for which weld bead is sound is strongly depended

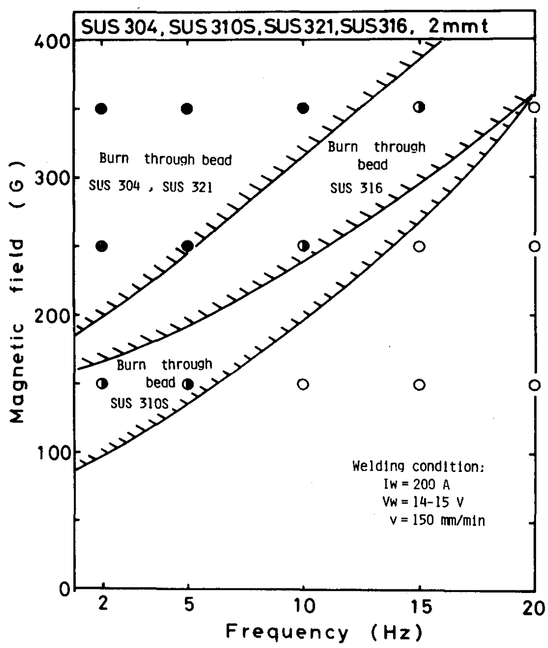


Fig. 3 Region of burn through bead as function of frequency and intensity of magnetic field.

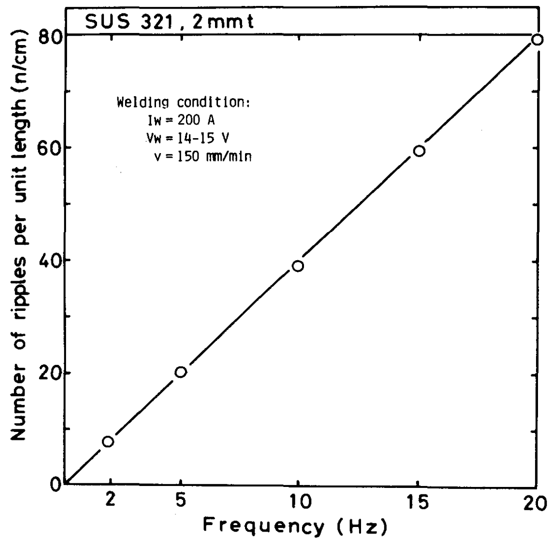


Fig. 4 Correlation between stirring frequency and number of ripples per cm.

on stirring frequency and kinds of steel. Increasing frequency can keep sound weld for high magnetic field. This is due to low speed of fluid flow in molten pool when higher frequency is applied. Moreover increasing of magnetic field in case of SUS 304 and 321 is estimated to be depended on surface tension of molten metal and on melting temperature.

Regular surface ripples are obviously seen on the weld bead when stirring is applied. **Figure 4** shows correlation between stirring frequency and number of ripples per cm in 150 mm/min welding speed. This result shows a precise movement of fluid flow in molten metal according to stirring frequency.

3.1.2 Optimum stirring condition for grain refining

Figure 5 shows an example of structural change of bead surface in SUS 304 steel weld (200A – 150 mm/min) under a correlation between stirring frequency and magnetic field during welding.

Lower photograph shows that of unstirred condition. As a result, it was cleared that the optimum condition exists for frequency, about 10 Hz in this case, and the higher magnetic field is effective for making fine grain. This is quite similar to that of aluminum alloys. Comparisons of metallographic examination for both weld bead surfaces of the unstirred and the most fine grained are shown for each steel in **Fig. 6 (a)** to **(d)**. In the most fine grained bead surface of each steel there are equiaxed dendrite crystal zone in the center of weld, though columnar crystals grow as cellular dendrite mode near fusion boundary zone. Of these steels it is observed that SUS 321 can make fine grains easier than the other steels.

Next the authors have tried to show linear ratio of equiaxed dendrite zone to weld bead width, in order to evaluate the degree for making fine grain in each steel quantitatively. **Figure 7 (a)** to **(d)** shows the result for

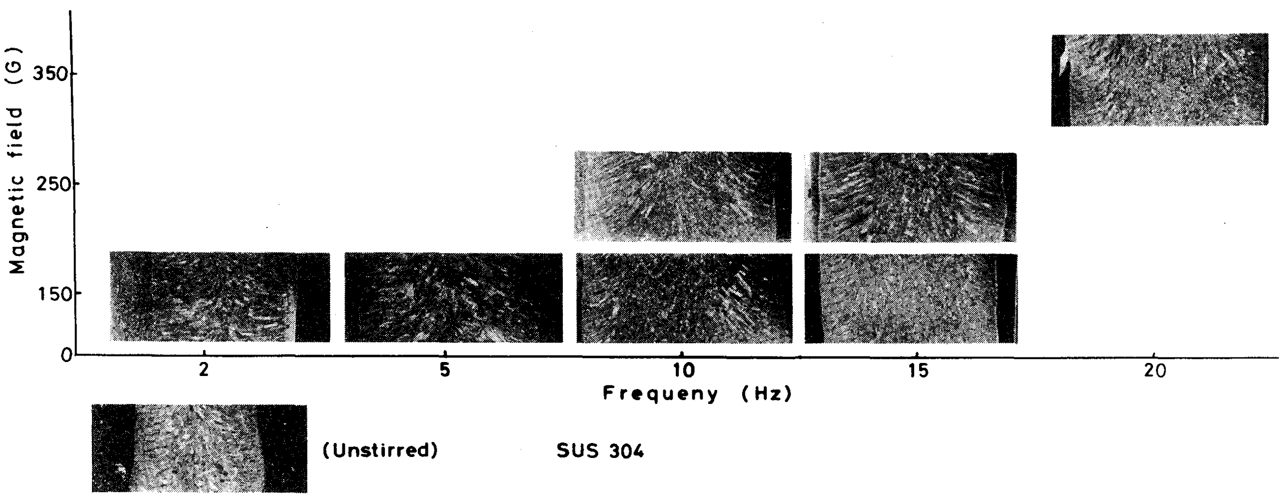
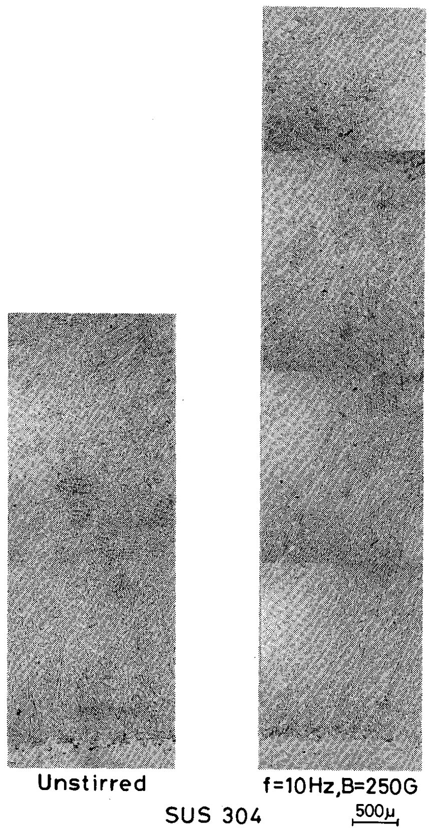
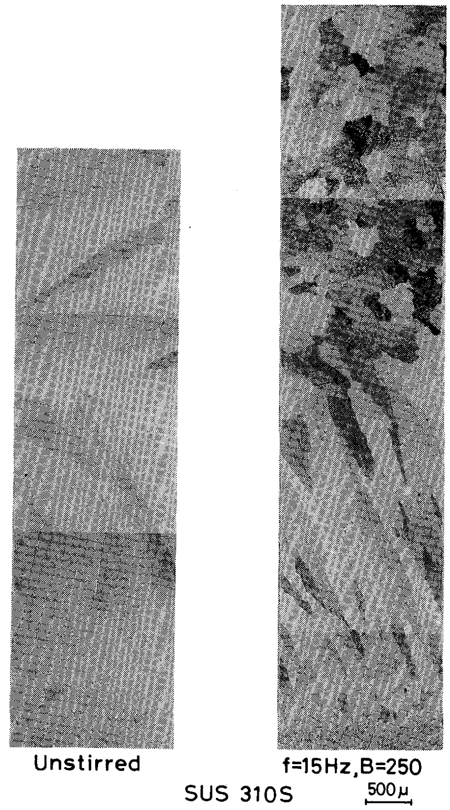


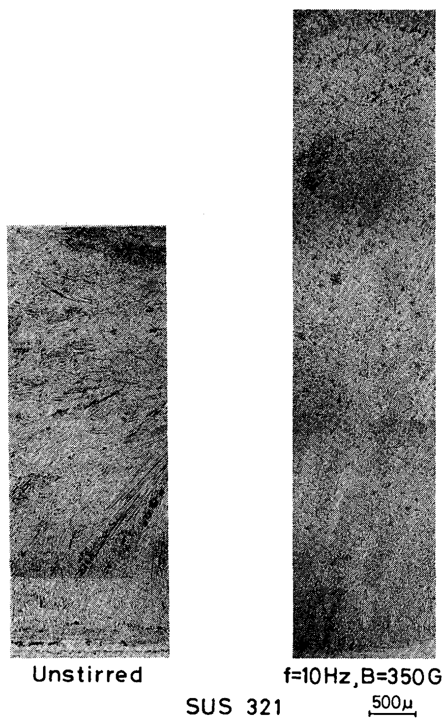
Fig. 5 Macrostructure of SUS 304 weld metal as functions of frequency and intensity of magnetic field, 200A-150 mm/min.



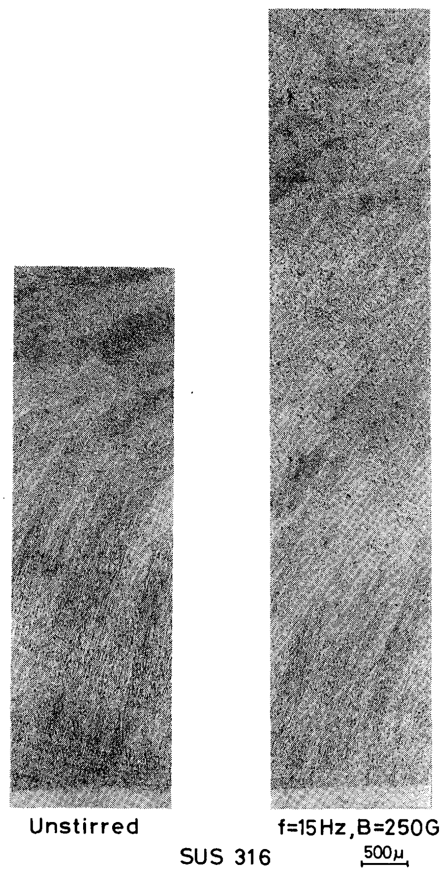
(a) SUS 304



(b) SUS 310S



(c) SUS 321



(d) SUS 316

Fig. 6 Typical macrostructure of weld bead surface, 200A-150 mm/min.

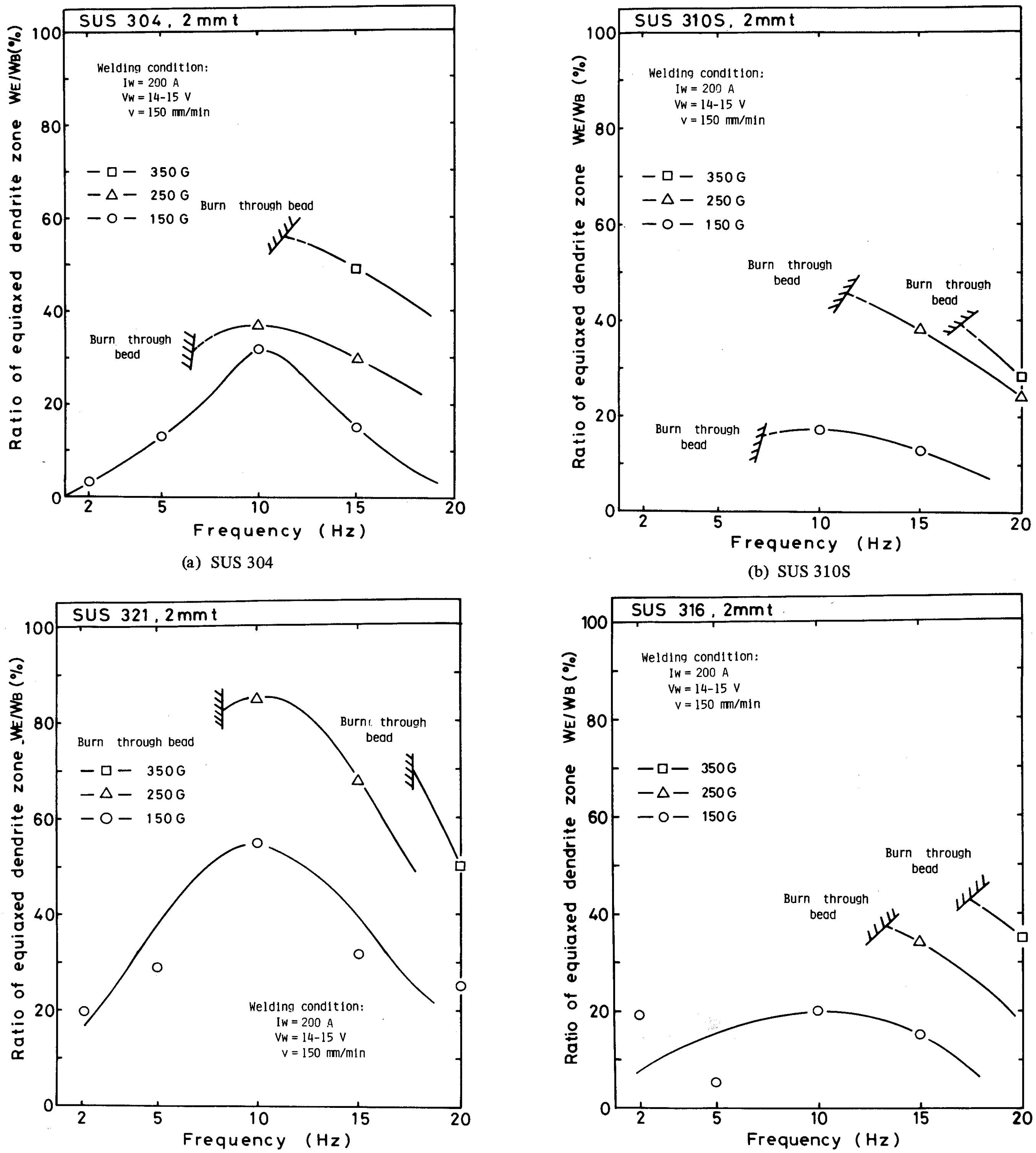


Fig. 7 Variation of degree of grain refinement in relation to stirring frequency and magnetic fields.

each steel against frequency for three intensities of magnetic fields. W_E and W_B show linear lengths of equiaxed zone and weld bead width in crossing the weld line, respectively. As a result, the optimum frequency is seen near 10 Hz for making fine grain, and the order in easiness is SUS 321, 304 and 310S ≒ 316. In case of SUS 321 2 mm thin steel about 60% and more than 80% of whole bead width could be changed to equiaxed crystals at 10 Hz under 150G and 250G, respectively. Furthermore, in order to avoid the burn through bead in case of thin sheet, higher frequency and higher magnetic field should be selected for making fine grain in general.

3.1.3 Effect of stirring variables on grain refining

(a) frequency

Figure 8 shows the change in surface structure of SUS 321 weld bead with changing of stirring frequency under the same magnetic field of 150G in welding condition of 200A – 150 mm/min. Each photograph shows the range from fusion boundary to center of bead. At the unstirred weld bead there is no equiaxed crystal in the center of bead, although the weld bead width is the narrowest comparing with the other beads stirred. At 2 and 5 Hz of stirring frequency the equiaxed crystal zone is increased in the weld bead with frequency although columnar crystal zone exists considerably near fusion zone. At 10 Hz the equiaxed crystal zone is the widest and the columnar zone exists only near fusion zone. However at 15 and 20 Hz the equiaxed zone is decreased comparing with that at 10 Hz. **Figure 9** shows the enlarged photograph near the fusion boundary zone in 2 Hz stirring bead of Fig. 8. Solid lines at both sides of the photograph indicate the ripples generated by the instant of reverse fluid flow. At the ripple line the growth direction of columnar crystal is changed obviously and shows zigzag growth as a whole. This reverse fluid flow will make equiaxed crystal inwards bead as a result of dendrite fragmentation. However the fluid flow force or speed sill be decreased with an increase in stirring frequency under the same magnetic field, though the number of times for changing flow direction is increased. This results in existence of the optimum frequency for making fine grain.

Next the authors have observed the state of grain

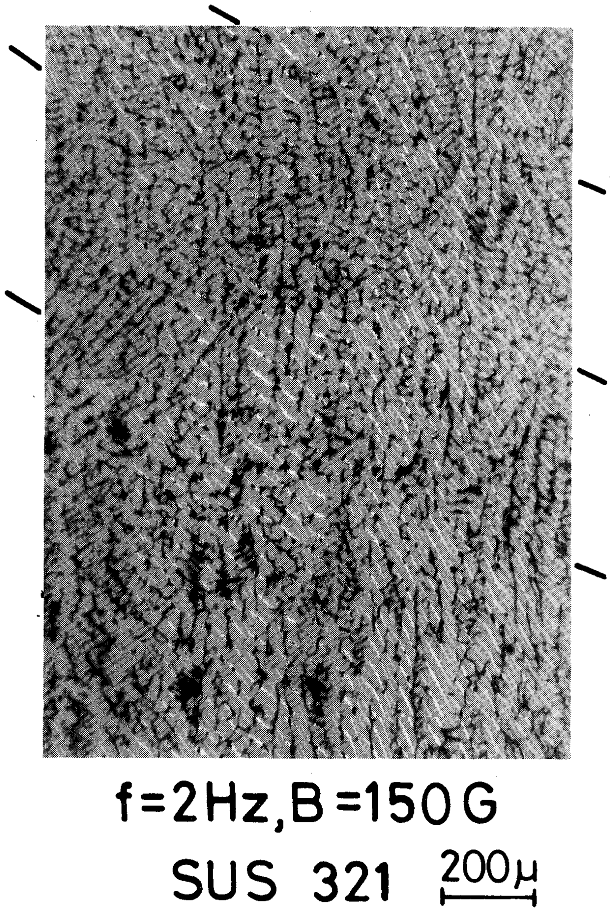


Fig. 9 Change in microstructure of weld metal of SUS 321 corresponding to weld bead ripples, 200A-150 mm/min.

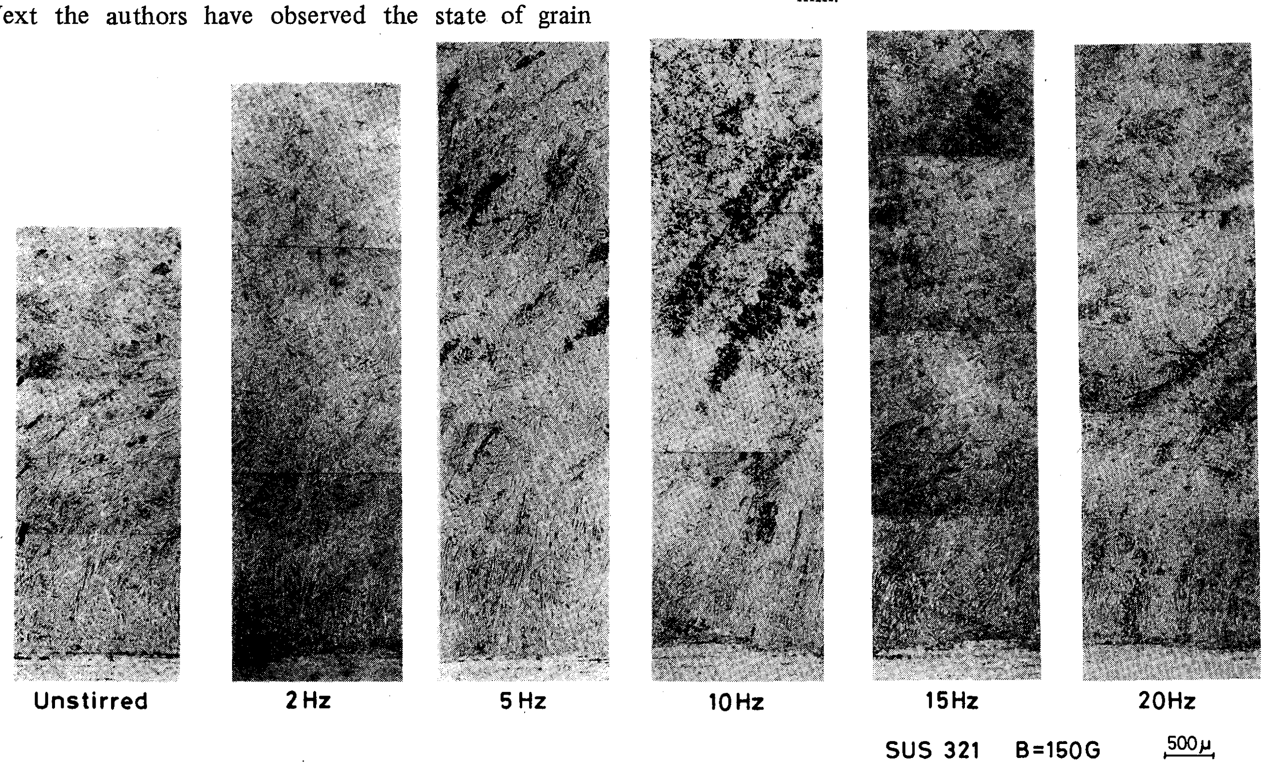
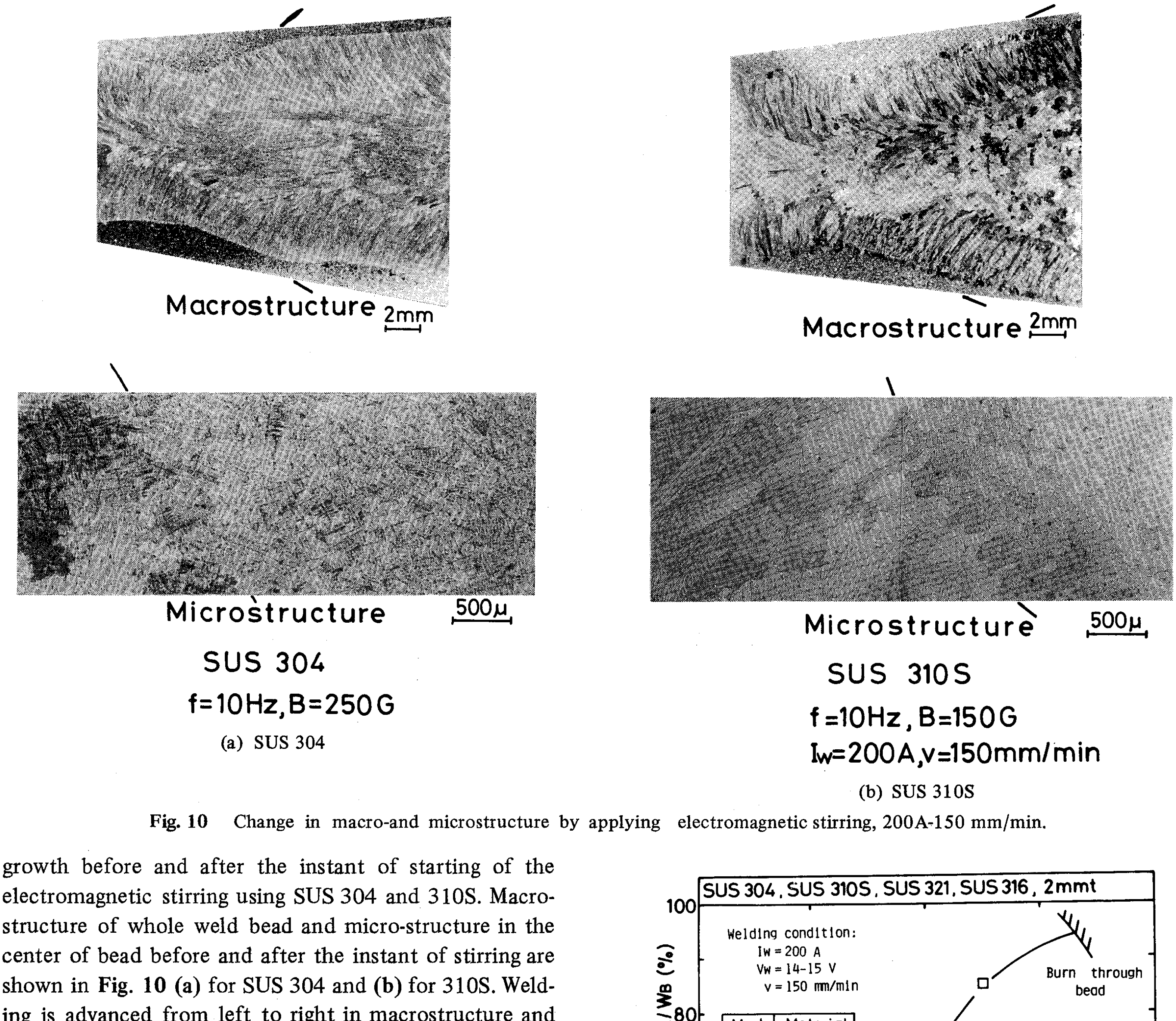


Fig. 8 Macrostructure of weld bead surface in various stirring frequency in SUS 321, 2 mm sheet, 200A-150 mm/min, 150G.



(a) SUS 304

(b) SUS 310S

Fig. 10 Change in macro-and microstructure by applying electromagnetic stirring, 200A-150 mm/min.

growth before and after the instant of starting of the electromagnetic stirring using SUS 304 and 310S. Macrostructure of whole weld bead and micro-structure in the center of bead before and after the instant of stirring are shown in **Fig. 10 (a)** for SUS 304 and **(b)** for 310S. Welding is advanced from left to right in macrostructure and bead width is gradually increased after the instant of start of stirring. From macrostructural observation equiaxed crystal zone near weld center is rapidly increased after the instant of start of stirring with increasing of bead width. Microstructural investigation shows an abrupt change in crystal mode from columnar to equiaxed crystal at the solid line which shows a ripple and the instant of start of fluid flow by stirring. The same phenomena was observed also in aluminum alloy indicated by the authors[1,2]. Therefore it is considered that new nucleation by fragmentation also occurs in stainless steel weld metal when the fluid flow in molten pool is reversely changed.

(b) magnetic field

Figure 11 shows effect of magnetic field on the ratio of equiaxed dendrite zone, W_E/W_B, for various steels under 10 Hz of frequency. An increase in magnetic field increases the ratio for all steels. It is understood that an increase in magnetic field increases the force of fluid flow

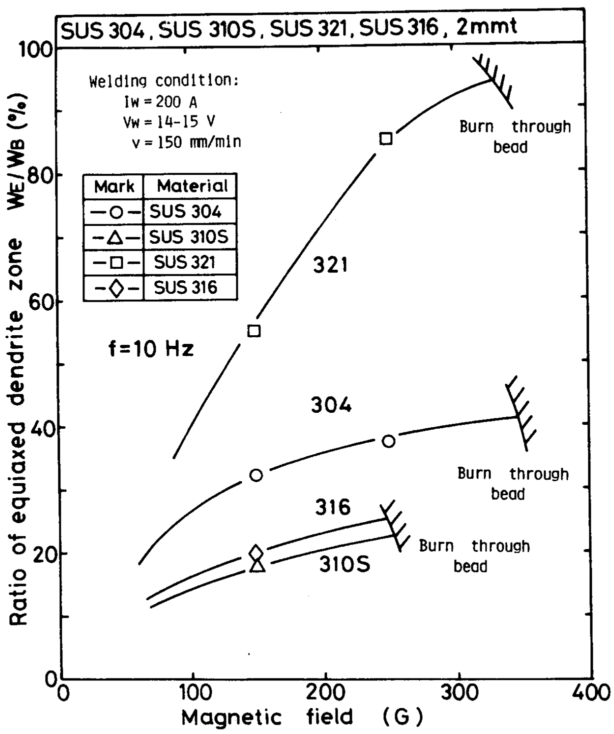


Fig. 11 Relation between degree of grain refinement and intensity of magnetic field, 200A-150 mm/min.

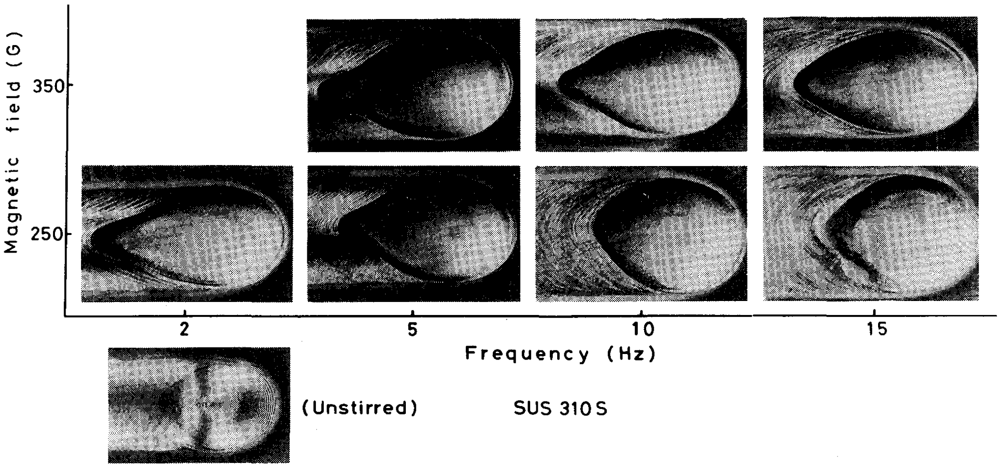


Fig. 12 Shape of molten pool as functions of stirring frequency and intensity of magnetic field in SUS 310S, 300A-150 mm/min.

in molten pool which makes fragmentation of the tip of growing dendrite. This effect obviously influences in case of SUS 321. From Fig. 11, the stronger the magnetic field, the larger the ratio of equiaxed zone. However, there is a limit in intensity of magnetic field for thin steel because of burn through of weld bead. This limit in this experiment for 2 mm thick sheet is laid in maximum 300 – 350G for SUS 304 and 321, 200 – 250G for 310S and 316.

3.1.4 Effect f kind of steel on grain refining

The effect of making fine grain is much stronger in SUS 321 than in 304 as shown in Fig. 11, although there is no difference in chemical compositions between them except content of Ti. The effect of adding Ti is considered that the equilibrium distribution coefficient of Ti in delta-iron during solidification is much smaller (0.40) than that of Cr (0.95), Ni (0.83), Mn (0.90) and Si (0.83)[3], consequently the roots of the secondary dendrite arm branched from the primary arm is become more slender due to higher segregation[4]. Therefore it is believed that the fragmentation of the tip of dendrite arm is much easier by an abrupt change in fluid flow in case of SUS 321 including Ti.

However this mechanism should be confirmed by in-situ observation technique in future for rapid solidification as welding.

3.2 Results for 8 mm thick plate

The technical knowledge for making fine grains which was obtained in thin steels was applied for partial penetration weld bead of thick plate as 8 mm in thickness.

3.2.1 Effect of electromagnetic stirring on configurations of bead and crater

Figure 12 shows change in appearance of bead crater in relation between frequency and magnetic field. The appearance of crater which was unstirred during welding shows no cave and rather flat surface and elliptical shape, however those which were stirred show a cave and undercut with rough bead which is gradually getting severe with an increase in magnetic field. Moreover the shape of crater is gradually getting near teardrop-shaped. Those tendencies are obvious as frequency is lower.

Effect of frequency on crater configuration is shown in **Fig. 13** as L/Lo, where L and Lo are longitudinal and transverse lengths of crater surface respectively. The dotted line of 1.25 in vertical axis shows the shape of unstirred crater. Decreasing frequency less than 10 Hz and increasing magnetic field shows slender shape, which

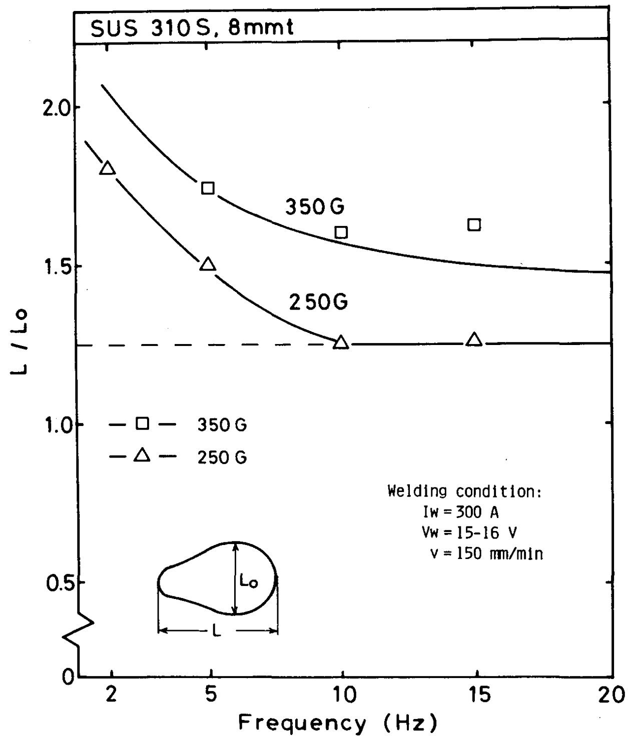


Fig. 13 Variation of crater configuration in cases of various frequency conditions of magnetic field for 250 and 350G.

means getting severer fluid flow and carring it away to rearside of the crater. However the shape of crater more than 10 Hz in frequency under 250G is quite similar to that of the unstirred crater.

Figure 14 shows the configuration of crosssectional bead in relation between frequency and magnetic field. In comparison with unstirred bead all beads show a deeper penetration regardless of frequency, though the bead width is not so changed. Moreover an increase in magnetic field deepens the penetration. This is considered to be caused by agitation of fluid flow and increasing of weld heat input due to extended arc column.

3.2.2 Effect of stirring variables on grain refining

The authors have investigated the degree of fine grained zone on crosssectional weld beads, in order to evaluate the effect of magnetic stirring. **Figure 15** shows the comparison in longitudinal crosssection between unstirred and stirred beads with 10 Hz-350G under a welding condition of 300A-150 mm/min for SUS 304, 310S and 321 steel plates. In unstirred bead there is an obvious equiaxed zone near the top of the bead although the depth of the zone is different in kind of steel. However the degree for making fine grains is generally considered to be less in thick plate than in thin sheet under the same stirring condition.

Figure 16 (a) to (c) shows an example of quantitative estimation of the equiaxed zone in crosssectional bead under 300A-150 mm/min for SUS 304, 310S and 321. Vertical axis shows ratio of equiaxed dendrite zone, D_E/D_B, where D_E and D_B represent the depths of equiaxed zone in bead and of bead in crosssection, respectively. The optimum frequency for making fine grains is laid between 10 to 5 Hz, which is roughly the same to the potimum in welding of thin sheet. Also the stronger the magnetic field, the better the effect for making fine grains.

Moreover, in order to investigate the effectiveness of much stronger magnetic field, the degree of equiaxed zone has been investigated up to 700G for SUS 310S using both upper and lower magnetic coils. **Figure 17** shows the result of the investigation and indicates that equiaxed zone in bead can be expanded to about 50% at 700G-5 Hz. **Figure 18** shows the crosssectional appearance of weld bead at 700G-5 Hz comparing that of unstirred one. An increase in magnetic field shows an increase in equiaxed crystal zone in weld bead of thicker plate. However the bead roughness is getting worse as a result. This requires further research in future.

Next, effect of reduction in welding heat input on equiaxed zone has been investigated using SUS 310S. Welding was done with 200A-300 mm/min for 5 and 10 Hz in 300G. However, there was no equiaxed grain zone near top area of the weld beads within the limits of the above welding conditions. Therefore for the purpose of grain refinements higher welding heat input is considered to be introduced better results.

4. Conclusions

The probability of grain refinement with electromagnetic stirring during GTA bead-on-plate welding has been investigated for commercial, austenitic stainless steels of SUS 304, 310S, 321 and 316. The maximum limits of stirring condition is 350G and 20 Hz under a 200A-150 mm/min for 2 mm thick sheets and is 700G and 15 Hz under 300A-150 mm/min and 200A-300 mm/min for 8 mm thick plates. As a result the following conclusions are obtained;

(1) The equiaxed dendrite zone which is produced near the center of weld bead for 2 mm thin sheet and near the surface of weld bead for 8 mm thick plate is observed for all steels by application of electromagnetic stirring.

(2) It is estimated that there is an optimum condition in stirring frequency in order to make fine grain effectively. The optimum frequency is observed in 5 to

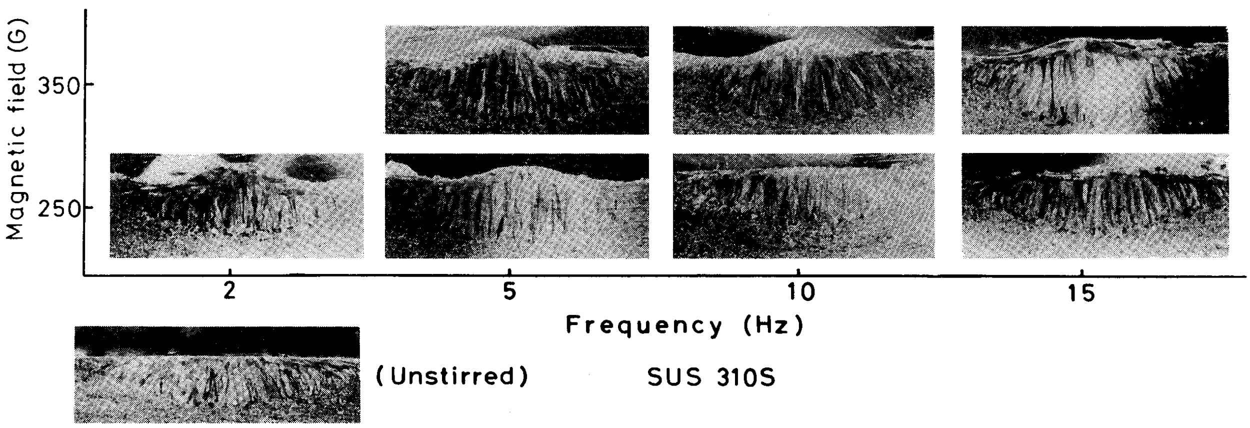
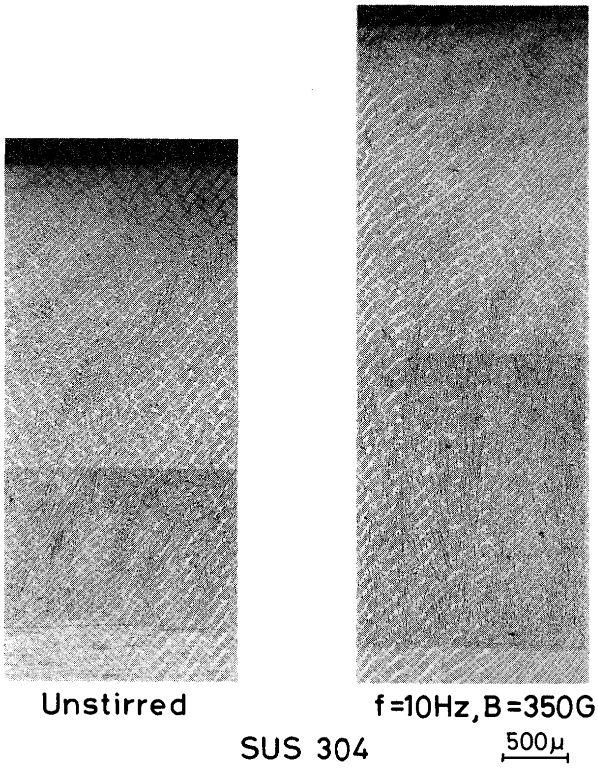
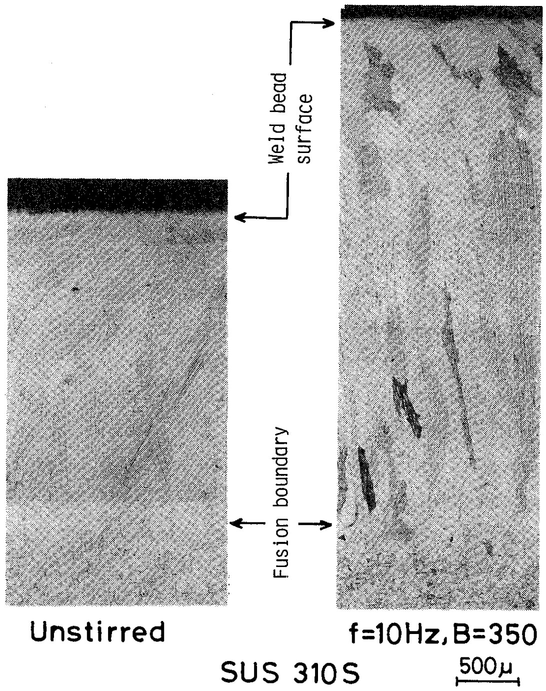


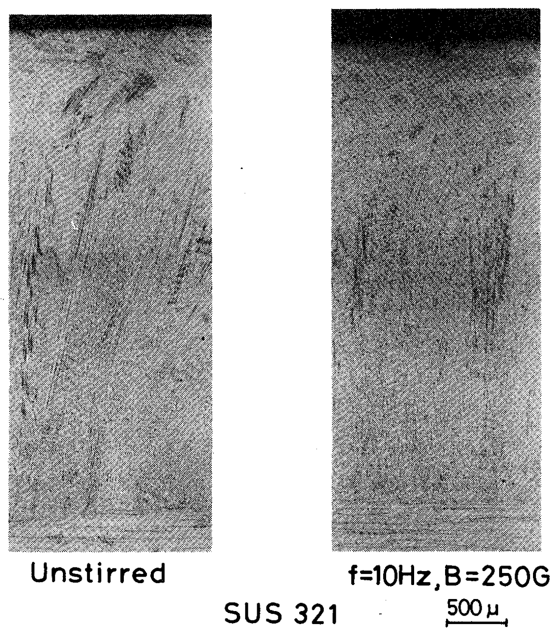
Fig. 14 Crosssection of SUS 310S weld bead in relation to stirring frequency and intensity of magnetic field, 300A-150 mm/min.



(a) SUS 304

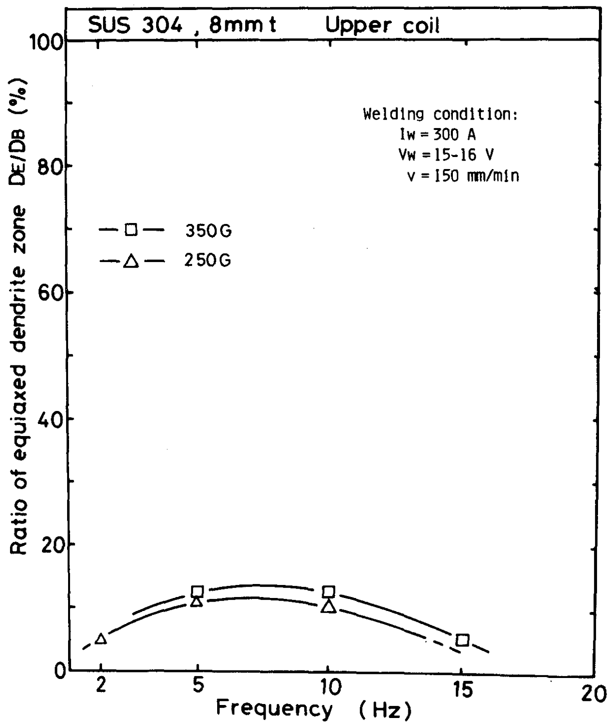


(b) SUS 310S

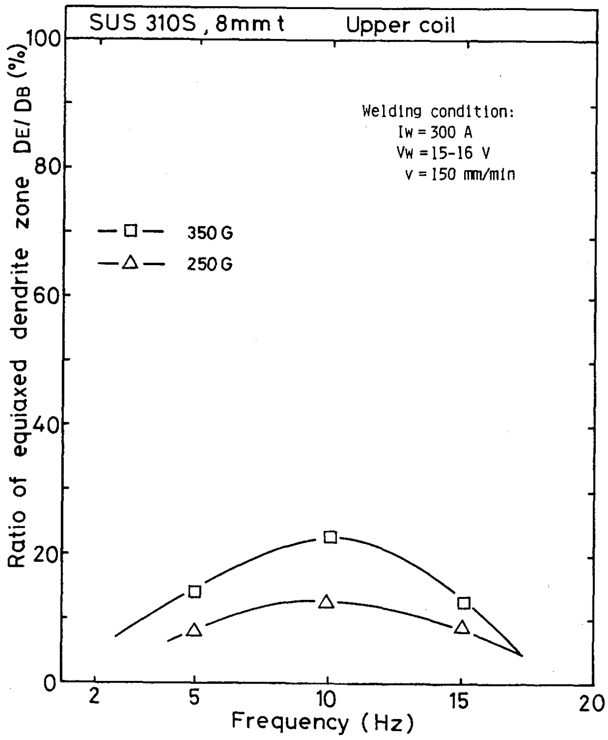


(c) SUS 321

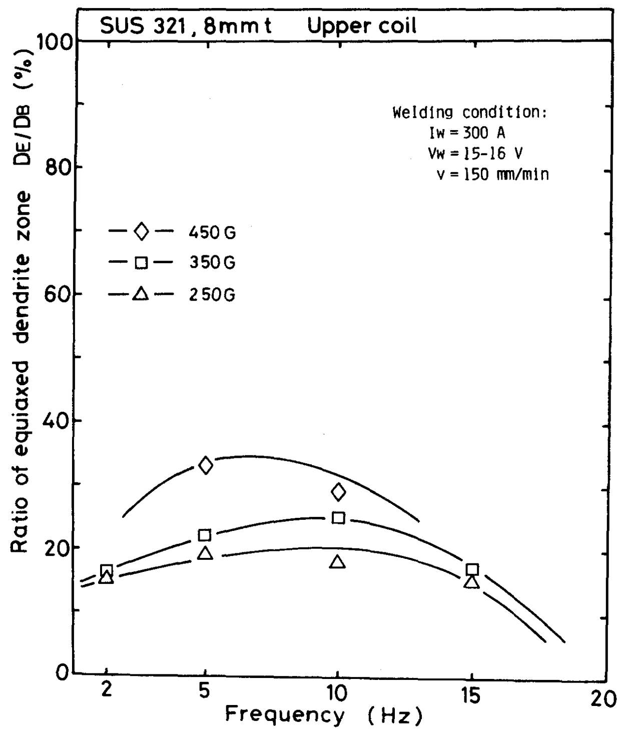
Fig. 15 Typical macrostructure of longitudinal crosssection of weld bead with and without stirring (10 Hz, 350G), 300A-150 mm/min.



(a) SUS 304



(b) SUS 310S



(c) SUS 321

Fig. 16 Variation of degree of grain refinement in relation to stirring frequency and magnetic fields, 300A-150 mm/min.

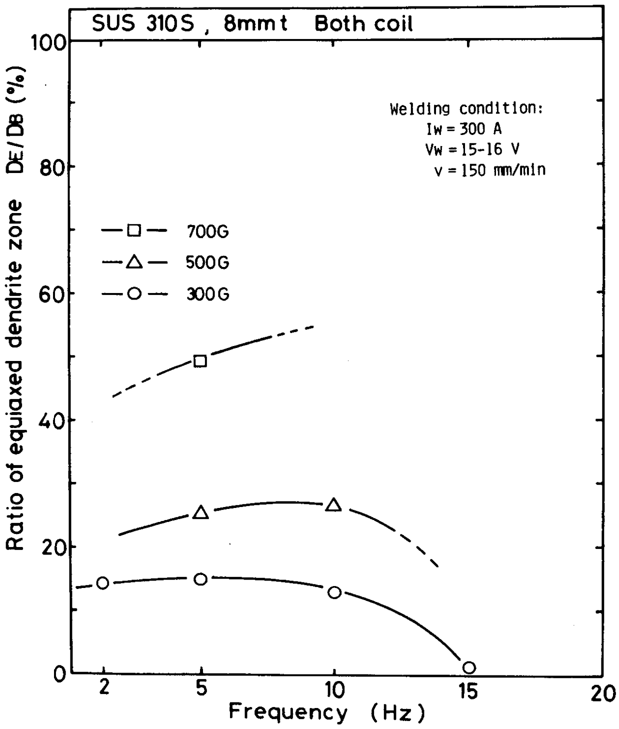


Fig. 17 Variation of degree of grain refinement in relation to stirring frequency and stronger magnetic fields, 300A-150 mm/min in SUS 310S.

10 Hz within a limit of this investigation. Moreover, in relation to magnetic field the stronger is the better for making fine grains. However there was a limit for electromagnetic stirring, because weld bead was burnt through for thin sheet and was getting rough in surface when high magnetic stirring was applied. This result was quite similar to that for aluminum alloys which was introduced by the authors[2].

(3) The degree of equiaxed zone produced is strongly depended on the kinds of steel, that is to say, the easiness rank for making fine grains is SUS 321, 304 and 310S and 316. Addition of Ti element makes fine grains easier, which is considered due to low distribution coefficient during solidification.

(4) Under the same stirring condition the grain refinement for thicker plate is harder than that for thiner sheet. In order to improve the refinement for thicker plate, increases in magnetic field and weld heat input are required under the frequency of 5 to 10 Hz. This is contrary to smoothness of bead surface. Therefore the further investigation is required for the compatibility.

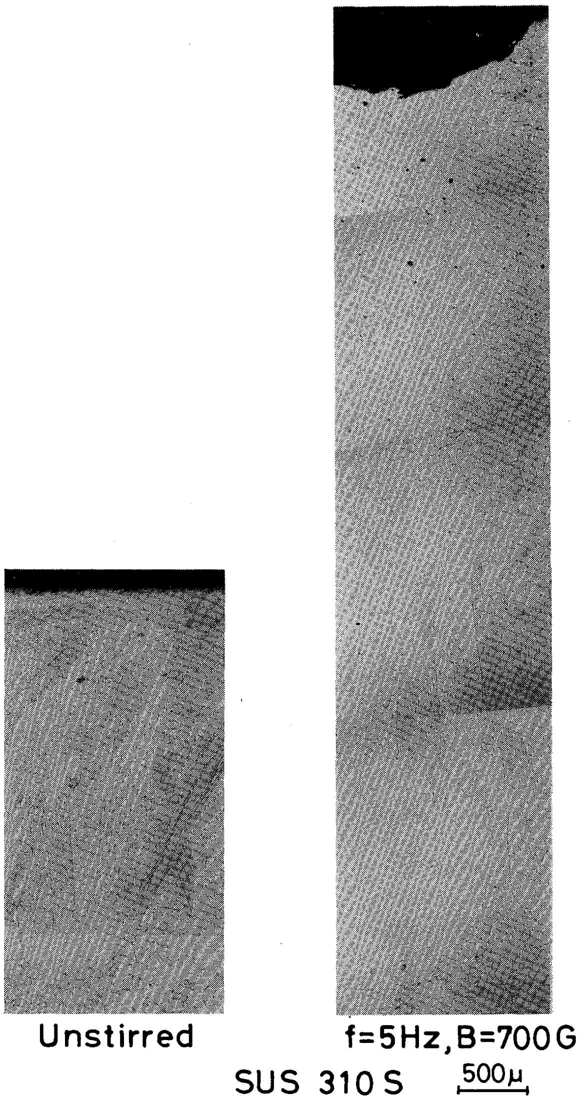


Fig. 18 Typical macrostructure in longitudinal crosssection of weld bead, 300A-150 mm/min, 700G.

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