STUDIES ON CHARACTERISTICS OF FRICTION STIR WELDED JOINTS IN STRUCTURAL THIN ALUMINIUM ALLOYS PART 2: METALLURGICAL FEATURES AND MECHANICAL PROPERTIES OF FRICTION STIR WELDED JOINTS

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ABSTRACT

Metallurgical features and mechanical properties of friction stir welded (FS-welded) joints under the combination of 5083, 6N01 and 7N01 alloys of 3 mm thick parent materials by two or three fabricators and four ways of procedures and also difference in these characteristics due to dissimilarities were studied. Shapes and structures of FS-welded zone, and their hardness distribution, etc., were clarified and these profiles were put in order according to these combinations. Some convenient means such as a measure to estimate these profiles were examined. The dissimilarities were clearly reflected in the hardness distributions, and the distributions to be considered suitable were obtained under their specified combinations. Joint efficiencies were obtained of about 100 % in 5083 joints, about 85 % in 6N01 joints except in some joint and about 96 % in 7N01 joints. All of 5083 joints bent till the minimum former diameter of 12 mm. Almost all of 6N01 joints bent till 32 mm but only the specified joint bent till 20 mm. Almost all of 7N01 joints bent till 20 mm but still only the specified joint was no less than 32 mm. Difference due to dissimilarities was recognized partly in the tensile properties and limitedly in the bendability.

IIW-Thesaurus keywords: *Friction stir welding; Friction welding; Aluminium alloys; Light metals; Hardness; Elongation; Bend strength; Mechanical properties; Strength; Practical investigations; Comparisons.*

1 INTRODUCTION

In Japan these days, since the adoption of Friction Stir Welding (FSW) process, the industrialization and development of the application technology have showed striking advances. Keeping step with this situation, and with a diversity of requests have hitherto been gathered under the Japan Light Metal Welding & Construction Association. In response to these needs, this association launched, in autumn 2002, the FSW sub-committee in the welding procedure committee as the research working organization on FSW procedure technology.

Here, this committee attempted to conduct not only a collection of information through the review of the relevant literature, and the adjustment, but also the core program studying of the characteristics of welded joints under the combination of the same alloy for parent materials by various fabricators and various ways of FSW procedures. These results were put in order according to the materials and also FSW procedures and it was studied whether any difference caused by dissimilarities in both of them was recognized or not.

Structural alloys were preferentially selected for test parent materials, with 3, 8 and 20 mm thickness scheduled, and were, or will be, fabricated by two or three companies, respectively. FSWs were executed by four companies for each parent material. The joint type was set with limits to butt joint. The other conditions were at the company's peculiar convenience but the up-to-the-minute technology of procedure was settled to be adopted. The experimental items are as follows:

– study on precision non-destructive testing,
– observation of metallurgical features of FS-welded zones,
– study on mechanical properties of FS-welded joints,
– measurements of residual stress and distortion,

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– comparison with properties of conventional TIG & MIG arc welded joints, as needed.

Results on characteristics of FS-welded joints in parent materials with relatively thinner 3 mm thickness are described in this report, “Studies on characteristics of friction stir welded joints in structural thin aluminium alloys”, composed of the following parts:

Part 1: Imperfections in friction stir welded zones and their precision non-destructive testing

Part 2: Metallurgical features and mechanical properties of friction stir welded joints

In Part 1, experimental results on imperfections in FS-welded zones and their precision non-destructive testing were shown. In this paper, the authors report study on metallurgical features and mechanical properties of FS-welded joints.

2 EXPERIMENTAL PROCEDURES

2.1 Test materials

5083-O, 6N01-T5 and 7N01-T5 alloys with 3 mm thickness were prepared for parent materials, which were fabricated by two and three companies, respectively. The chemical composition and mechanical properties are shown in Tables 1 and 2.

Table 1 – Chemical composition of parent materials

Materials		Chemical Composition [%]										
Alloy-Temper	Manufacturing number	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	V	Al
A5083P-O	Requirement	≤ 0.40	≤ 0.40	≤ 0.10	0.40 to 1.0	4.0 to 4.9	0.05 to 0.25	≤ 0.25	≤ 0.15			re.
	51	0.06	0.20	0.03	0.70	4.46	0.09	0.02	0.01			re.
	52	0.15	0.20	0.02	0.68	4.61	0.11	0.00	0.02			re.
A6N01S-T5	Requirement	0.40 to 0.9	≤ 0.35	≤ 0.35	≤ 0.50	0.40 to 0.8	≤ 0.30	≤ 0.25	≤ 0.10			re.
	61	0.55	0.23	0.10	0.07	0.69	0.04	0.01	0.02			re.
	62	0.80	0.20	0.00	0.20	0.50	0.00	0.06	0.01			re.
	63	0.54	0.17	0.02	0.04	0.55	0.00	0.00	0.00			re.
A7N01S-T5	Requirement	≤ 0.30	≤ 0.35	≤ 0.20	0.20 to 0.7	1.0 to 2.0	≤ 0.30	4.0 to 5.0	≤ 0.20	≤ 0.25	≤ 0.10	re.
	71	0.07	0.14	0.05	0.64	1.07	0.00	4.48	0.02	0.18	0.010	re.
	72	0.12	0.21	0.15	0.40	1.25	0.08	4.56	0.02	0.14	0.008	re.
	73	0.05	0.18	0.14	0.37	1.00	0.01	4.11	0.02	0.17	0.010	re.

Table 2 – Mechanical properties of parent materials

Materials		Mechanical properties						
Alloy-temper	Manufacturing number	Tensile strength [Mpa] //	⊥	Yield strength at 0.2 % offset [Mpa] //	⊥	Elongation [%] GL50mm //	GL25mm ⊥	Hardness in Vickers hardness [HV5]
A5083P-O	Requirement	275 to 355		≥ 125		≥ 16.0		
	51	312 [313,311,312]	309 [307,308,311]	146 [146,145,146]	146 [145,146,147]	24.3 [25.4,23.3,24.2]	25.3 [25.7,25.3,25.0]	78.4
	52	315 —	308 —	152 —	149 —	24.9 —	25.7 —	76.7
A6N01S-T5	Requirement	≥ 245		≥ 205		≥ 8.0		
	61	288 [288,287,288]	281 [281,280,280]	264 [265,263,266]	241 [240,242,242]	9.7 [10.0,9.6,9.6]	12.8 [12.8,12.8,12.8]	102.7
	62	290 [287,291,292]	283 [283,284,283]	270 [268,271,271]	257 [259,257,256]	14.7 [15.1,15.2,13.8]	12.0 [12.0,12.1,11.9]	106.6
	63	263 [263,262,264]	258 [257,258,258]	233 [239,233,226]	233 [229,235,235]	14.3 [14.0,15.0,14.0]	13.7 [13.0,14.0,14.0]	96.6
A7N01S-T5	Requirement	≥ 325		≥ 245		≥ 10.0		
	71	430 [429,430,431]	429 [425,431,431]	377 [376,377,376]	387 [384,388,389]	14.5 [14.6,14.5,14.4]	16.1 [16.0,16.4,16.0]	129.7
	72	435 [435,435,435]	432 [433,433,432]	378 [377,378,379]	372 [372,380,363]	15.0 [15.0,14.6,15.4]	16.4 [16.4,16.8,16.0]	133.0
	73	378 [377,381,376]	377 [381,374,376]	320 [320,320,319]	323 [325,321,324]	12.4 [12.5,12.9,11.9]	17.8 [18.1,16.7,18.5]	112.7

From these tables, it was confirmed that all of them satisfied their requirements, it means, these were the same alloys for parent materials by various fabricators.

Friction stir welding (FSW) was executed by four companies in each parent material. These materials of 150 mm width and 333 or 500 mm length were FS-welded with square-butt preparation. The other conditions were at the company's peculiar convenience though some measured values among their conditions were clarified in order to calculate heat input parameter under-mentioned. These joints were subjected to not only current non-destructive testing but also ultrasonic phased array inspection, and welded joints with acceptable levels, through this testing, were supplied to studies on their characteristics. Conventional TIG and MIG arc welded joints, in the same parent materials above mentioned, produced by two companies, respectively, were also supplied for comparison with them, as needed.

The same numerical designation as that in Part 1 was used here to identify FS-welded joints or specimens, such as 5xx, 6xx and 7xx for 5083, 6N01 and 7N01 alloys for parent materials.

2.2 Experimental process

First, in order to furnish as many fundamental and metallurgical factors as possible, which will be predicted to affect various properties of FS-welded joints, observation of shapes and of macro- and micro-structures in FS-welded zones, and measurements of hardness distribution in these zones, etc., were carried out. In these stirred zones, the thickness at the centre of the welded joint: Tsz, the width at the centre of the joint thickness: Wsz, the cross-sectional area: Asz, and the surface and back widths: Ws and Wb, etc., were measured for references in discussion on properties of FS-welded joints, as shown in Figure 1. Moreover, the alloying elements included in the parent materials such as Mg, Zn and Si were analysed in the zones. Profiles of hardness in FS-welded zones, such as width of HAZ: W_{HAZ}, W_{HAZ}/Wsz, minimum hardness: Hmin and Hmin/Hp (Hp: hardness of parent material), were also measured, as defined in Figure 2.

And convenient means as a measure, from practical use, to estimate their profiles were examined.

Second, tensile properties were studied. In testing, five test specimens were prepared from the joints. Their specimens were located at distances of 50 mm, 120 mm, 190 mm, 260 mm and 330 mm from the end of welding start, where these five specimens are identified by the last digit of four-digit numerical designation such as xxx1

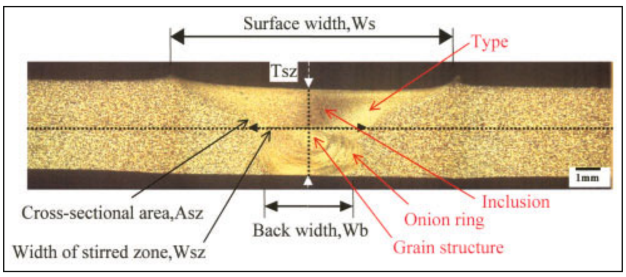

Figure 1 – Profile of friction stir welded joint

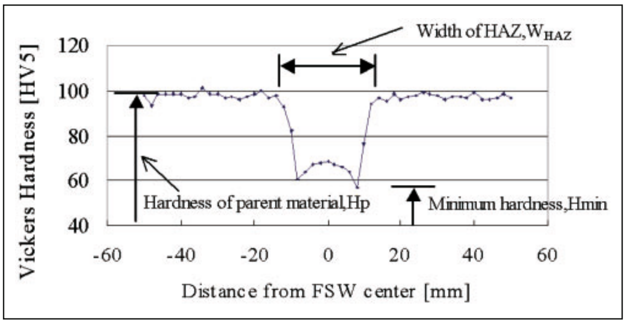

Figure 2 – Profile of hardness distribution in friction stir welded joint

to xxx5, respectively. 0.2 % proof strength was measured using a gage length of 50 mm. The elongation was measured using both gage lengths of 50 mm and 80 mm. The test method was almost subject to ISO 4136.

Third, bending properties were studied. Bend testing was carried out almost in accordance with ISO 5173, where test specimens were finished to 20 mm width with flashes of welded joints not dressed. Both face and root sides of FS-welded joints were examined in two or three test specimens for each former diameter. The minimum former diameter was estimated by occurrence of a flaw or a crack in the testing and the bendability was represented with the ratio of the diameter to thickness of the parent materials, *t*.

These results were put in order according to the parent materials and also FSW procedures and it was studied whether any difference caused by dissimilarities in both of them was recognized or not.

These experiments were carried out on FS-welded joints kept at room temperature about two months after their FSW.

3 RESULTS AND DISCUSSION

3.1 Profiles of friction stir welded zones and their structures

Typical macro-structures of cross-section of friction stir welded (FS-welded) zones are shown in Figure 3, for example.

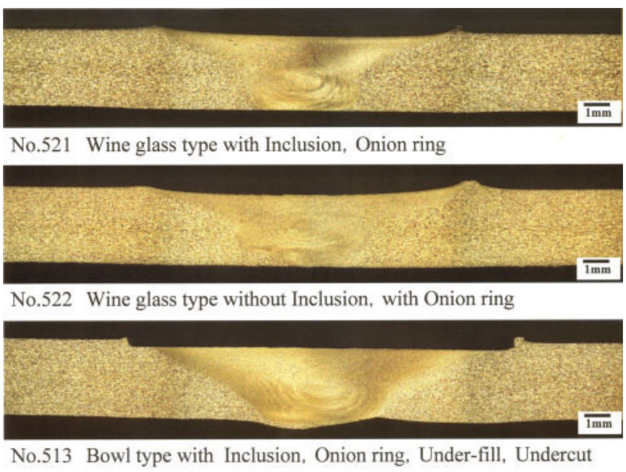

Figure 3 – Typical structures of cross-section in 5xx joints

In these figures, stirred zones with fine grain structures and flash at both sides were observed. The shape could be classified into three types such as a wine glass type: Y, a bowl type: B and a mixed type: M, and inclusions winding through and onion rings were recognized in some stirred zones. Under a FSW procedure, a stirred zone with under-fill or undercut was observed, too, as shown in specimen 513.

These results and values of Tsz, Wsz, Ws and Wb and Asz put in order for 5xx joints, are shown in Table 3, for example.

Here, the heat input parameter: *Q* which was calculated by equation (1) was adopted as a mean of measure to estimate degrees of heat inputs. This *Q* was modified from the equation introduced by Michael J. Russell *et al.* [1], where the peak surface temperature could be predicted.

$$Q = \sigma_{0.2}\omega R^2(1/vR)^{1/2} \quad (1)$$

where

$\sigma_{0.2}$: 0.2 % proof stress of parent material (MPa),
ω: rotational speed (rpm),
R: shoulder radius (mm),
v: travel speed (mm/s).

A Y type of stirred zone was observed under lower *Q* values, and under higher *Q* values onion rings were hardly observed, though it was not clear whether there was any difference caused by dissimilarities both in parent materials and in FSW procedures.

These types of shapes seem to be formed through stirring and heating by FSW tools. At the initial stage of FSW, the stirred zone is considered to be a "T" type formed by the tool composed of shoulder and probe, not observed here though, and then with the processing it will progress to a Y type and furthermore to a B type according to promotion of stirring and heating by this moving heat source and, in addition, the heat conduction. Therefore, a B type of stirred zone appears to need higher heat input than a Y type. While, onion rings seem to be a kind of distribution of alloying elements like solute bands observed in arc welding processes, so that the reason why onion rings were not observed appears to result from supply of enough heat inputs to diffuse these elements during FSW. Difference in types of stirred zones and occurrence of onion rings, thus, seem to depend on heat inputs during FSW. Then this parameter, *Q* value adopted here might be a certain measure to estimate degrees of heat inputs though moving heat source theory introduced by Rosenthal and Christensen *et al.* in arc welding process should be further studied in FSW, too.

Furthermore, Table 3 shows there were different *Q* values, according to FSW procedures, in order to produce suitable joints for the same parent material.

While, relationship between *Q* values and Ws, Asz, was examined because this value in itself was modified from the equation to predict peak temperature on stirred surface and also a contour of cross-sectional area was considered to represent a sort of iso-temperature face. Figure 4 shows the relationship in 5xx joints, where the values and symbols used are those shown in Table 3.

Ws and also Asz showed a good relationship between this heat input parameter in spite of dissimilarities in parent materials and FSW procedures. This parameter might, therefore, turn into a convenient mean as a measure to estimate these profiles, although more and more studies seem to be required to establish it, together with theorization in FSW mechanism. Another result to point out here is the difference in Asz observed under these combinations. It proved that the zone was stirred efficiently, that is, with relatively small areas and lower *Q* value, in order to produce proper quality of welded joints, under some combination of parent material and FSW procedure.

About 0.1 % decrease of Mg and about 0.1 % to 0.2 % decrease of Zn were analysed in some stirred zones.

Table 3 – Profile of stirred zone in 5xx joints

Specimen		Q	Profile						
			Shape					Others	
No.	Symbol	(E+06)	Tsz (mm)	Wsz (mm)	Ws/Wb (mm)	Asz (mm^2)	Type	Inclusion	Onion ring
511	◎	4.6	2.8	5.4	10.6/3.1	18	Y	O	O
512	◉	8.5	2.8	7.4	12.6/3.2	19	M	O	O
513	○	8.6	2.8	7.7	12.6/4.2	23	B	O	O
514	●	11.0	3.0	6.4	14.7/3.2	20	B	N	O
521	△	4.7	2.9	5.0	10.6/3.1	18	Y	O	O
522	▲	8.6	2.9	6.1	12.3/2.0	19	Y	N	O
523	△	8.8	3.0	7.3	12.8/3.4	23	B	O	O
524	▲	11.0	3.0	6.4	14.7/3.5	20	M	O	N

O: Observed N: Not observed

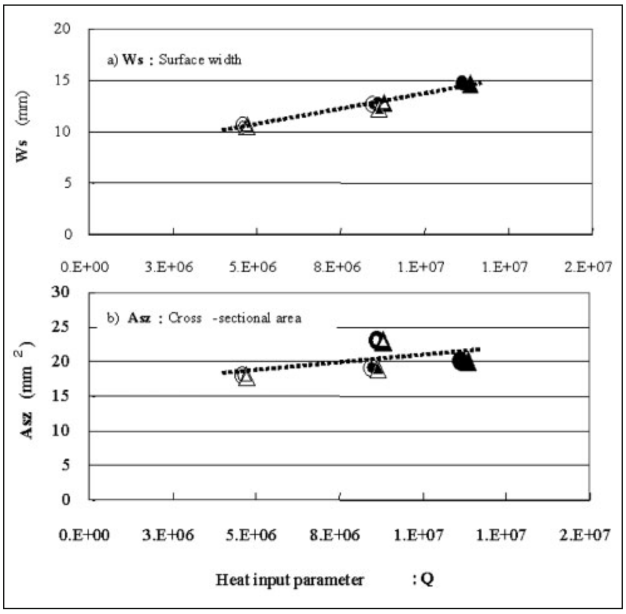

Figure 4 – Relationship between heat input parameter: *Q* and surface width, cross-sectional area in 5xx joints

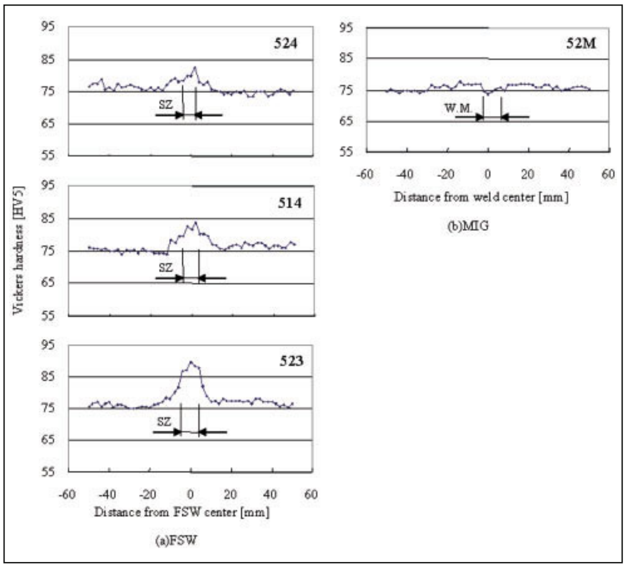

Figure 5 – Hardness distributions in welded zone in 5xx joints

Grain sizes of stirred zones and weld interfaces are shown in Table 4.

All of these grains were granular in the stirred zones. In those results, difference due to the dissimilarities was not clear though comparatively coarser grains were obtained in 6xx joints than in those of both 5xx and 7xx joints.

3.2 Hardness profiles in friction stir welded zone

Typical hardness distributions in FS-welded zones along the middle of their thickness for 5xx and 7xx joints are shown in Figures 5 and 6, respectively, where typical distributions at MIG arc welded joints are also shown for comparison with each other.

In 5xx joints, similar distributions were obtained in all of TIG and MIG arc welded joints as represented in (b) specimen 52M, where almost uniform distribution was obtained over the welded joints. On the other hand, hardness distribution in FS-welded zones differed from each other, depending on its parent material in spite of the same alloy, as shown in specimens 524 and 514, where in the former joints a nearly uniform distribution was obtained, while in the latter, hardening zone was

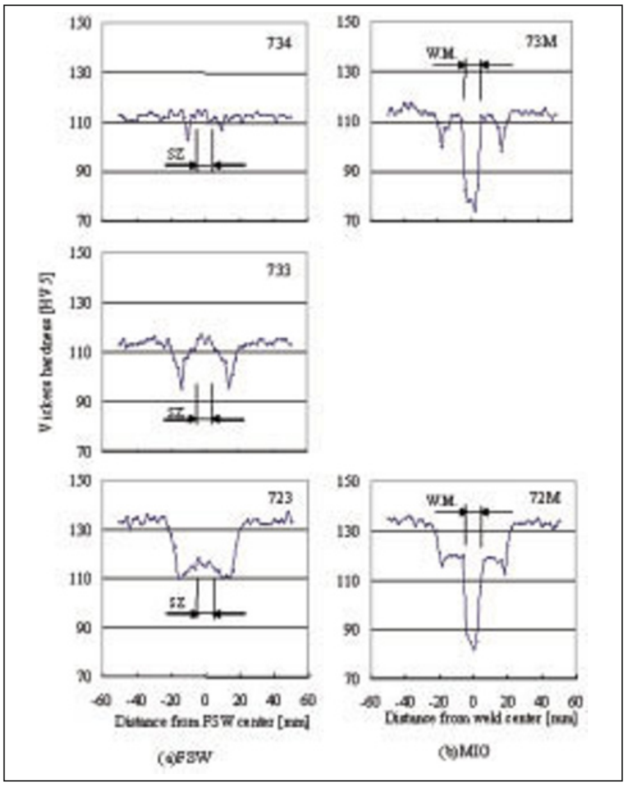

Figure 6 – Hardness distributions in welded zone in 7xx joints

Table 4 – Grain size of friction stir welded zones

Test specimen	Stirred zone		Interface		Heat input parameter *Q*
	Type	Size [μm]	Type	Size [μm]	
521	Granular	4	Granular	14	Low
523	Granular	4	Columnar	31	High
621	Granular	12	Granular	58	Low
623	Granular	7	Granular	53	Low
624	Granular	18	Granular	67	High
711	Granular	4	Granular	10	Low
713	Granular	4	Columnar	9	Low
714	Granular	4	Columnar	5	High

easily observed. Moreover, in specimen 523, the zone was hardened further highly and widely, where this distribution seemed to result from dissimilarities in FSW procedure between specimens 524 and 523. In these distributions, the difference caused by dissimilarities in parent materials and also FSW procedures was actualised clearly. From those results, it was concluded that these 5083 alloys for materials appeared to have already been so rationally designed in the alloying for parent materials of arc welding processes that almost similar hardness distributions might be obtained in the welded joints, even if these welding procedures were modified. On the other hand, in the case of FSW process, it proved that among these distributions in FS-welded zones, that of specimen 524 was regarded as suitable, that is, the specified combination of the parent material and the FSW procedure would produce the desirable distribution. These results are considered to suggest the primary factor to search after in order to study on developments of parent materials for FSW procedure and of the procedure as such.

In 7xx joints, similar distributions were still obtained in all of TIG and MIG arc welded joints as represented in (b) specimens 73M and 72M, where both natural-aged and over-aged zones in the joints were observed though their hardness values and also degree in natural-ageing differed from each other and this behaviour appeared to result from the way of alloying design. On the other hand, different hardness distributions were obtained in FS-welded zones according to the FSW procedure, in spite of in the same parent material. As shown in specimens 734 and 733, in the former joints, a nearly uniform distribution was obtained after natural-ageing, as post-weld heat treatment, while, in the latter, the zones not fully natural-aged were observed. Moreover, when only the parent material was changed, the zone widened further over the joint as shown in specimens 733 to 723. In these distributions, too, the difference caused by dissimilarities in parent materials and also FSW procedures was actualised clearly. From those results, the same conclusion as mentioned above was again clarified. And it proved, in the case of FSW process, that among these distributions in FS-welded zones, that of specimen 734 was regarded as suitable, that is, their specified combination would produce the desirable distribution, where only solutionizing and reversion were nearly suggested to occur during the FSW.

Hence, it follows that these results are considered to turn out such a valuable knowledge that any parallel case is scarcely caught sight of in the previous reports, in order to study on development of parent materials for FSW process and, in addition, FSW process in itself.

Profiles of hardness in FS-welded zones, such as W_{HAZ}, W_{HAZ}/Wsz, Hmin and Hmin/Hp, were put in order for references in discussions on properties of FS-welded joints. Table 5 shows the results obtained for 6xx joints.

Hardness distribution near the surfaces or roots, for example, will be able to infer from values of W_{HAZ}/Wsz and those of Ws or Wb. Here, Asz, was adopted as a mean of measure to estimate these profiles, where the contour was considered as a kind of iso-temperature face as mentioned before. The relationship with W_{HAZ} was thus examined, since W_{HAZ} was guessed to affect mechanical properties of FS-welded joints and its contour was also considered to represent a certain iso-temperature face though during FSW working by tool was added during FSW as suggested from Figure 5. Figure 7 shows the relationships for 6xx and 7xx joints.

In 6xx joints, a fairly good relationship appeared to be obtained, except in 6x3 joints with under-fill or undercut in their stirred zones, despite of dissimilarities in parent materials and also FSW procedures. So, this value, Asz might turn into a convenient mean as a measure to esti-

Table 5 – Profile of hardness distribution in friction stir welded zone of 6xx joints

Specimen		Profile				
		W_{HAZ}	Wsz	W_{HAZ}/Wsz	Hmin	Hmin/Hp
No.	Symbol	(mm)	(mm)		(HV5)	
611	◎	12	6.2	1.9	67.7	0.66
612	◉	12	6.1	2.0	70	0.68
613	○	12	8.2	1.5	65.2	0.63
614	●	16	8.0	2.0	67.7	0.66
621	⟁	12	6.7	1.8	67	0.63
622	◬	14	6.4	2.2	70	0.66
623	△	16	10.0	1.6	65.2	0.61
624	▲	16	8.4	1.9	69.6	0.65
631	⧈	14	6.0	2.3	61.6	0.64
632	▣	14	6.4	2.2	61.6	0.64
633	□	16	10.0	1.6	56.5	0.59
634	■	16	8.3	1.9	56.8	0.58

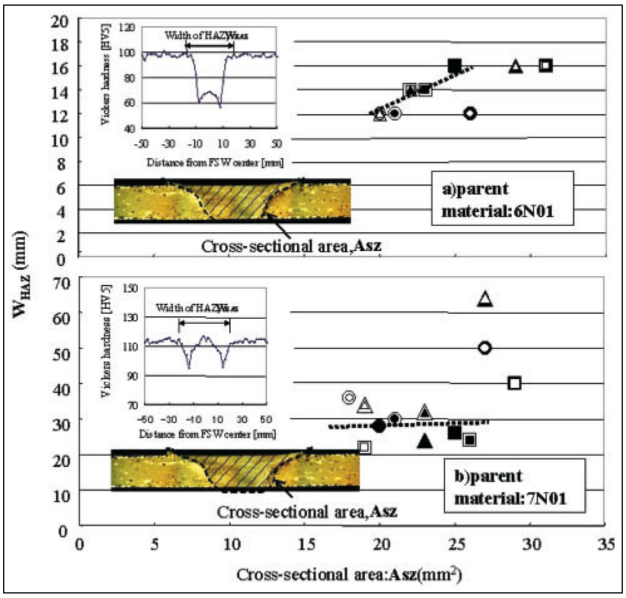

Figure 7 – Relationship between cross-sectional area and width of HAZ

mate width of HAZ. While, in 7xx joints, any good relationship could not be obtained, which seemed to result partly from the difference in hardness distribution caused by the dissimilarities, as shown in Figure 6.

After all, further research will be needed to clarify such means, from practical use of FSW procedure, as to estimate their profiles easily, together with theorization of FSW mechanism.

3.3 Tensile properties

3.3.1 5xx joints

Figure 8 shows tensile properties such as tensile and 0.2 % proof strengths, and elongation of 52x joints, as typical results of 5xx joints.

Their fracture positions are also shown there. The tensile strength was 300 to 326 MPa and the elongation was 13 to 21 % using a gage length of 50 mm. Difference caused by dissimilarities in FSW procedures was recognized in their fracture positions clearly and in their elongations slightly. Hardening zones observed in Figure 5 seem to affect their tensile properties hardly. However, slight decrease was recognized only in both strength and elongation of test specimens 523x despite higher hardness in their stirred zones compared with those of other joints. This reason was considered to result from stirred zones with under-fill or undercut, as shown in Figure 3.

A similar elongation, measured using a gage length of 50 mm, to that using a gage length of 80 mm was obtained, in spite of hardness distribution in the stirred zone shown in Figure 5.

Table 6 shows, for example, tensile properties of 51x joints put in order, where these are mean values in overall measurements and elongation using a gage length of 80 mm.

The averaged joint efficiency of about 100 % was obtained in 5xx joints. Difference in the tensile properties by dissimilarities in parent materials was hardly recognized.

These results seem to be such a valuable knowledge that any parallel case is scarcely caught sight of in the previous results and to form suitable information for backing-up on writing out draft standards.

Table 6 – Tensile properties of 51x joints

		Tensile strength MPa	0.2 % proof strength MPa	Elongation %	Joint efficiency %
51	Average	327	151	18	104
	Standard	6.4	3.1	3.9	---
512	Average	334	155	17.6	107
	Standard	1.8	1.8	0.9	---
514	Average	325	149	22.4	104
	Standard	2.1	0.9	0.6	---
511	Average	322	150	14.1	103
	Standard	6.7	1.9	2.9	---
513	Average	313	146	13.8	100
	Standard	3	2.6	1.2	---

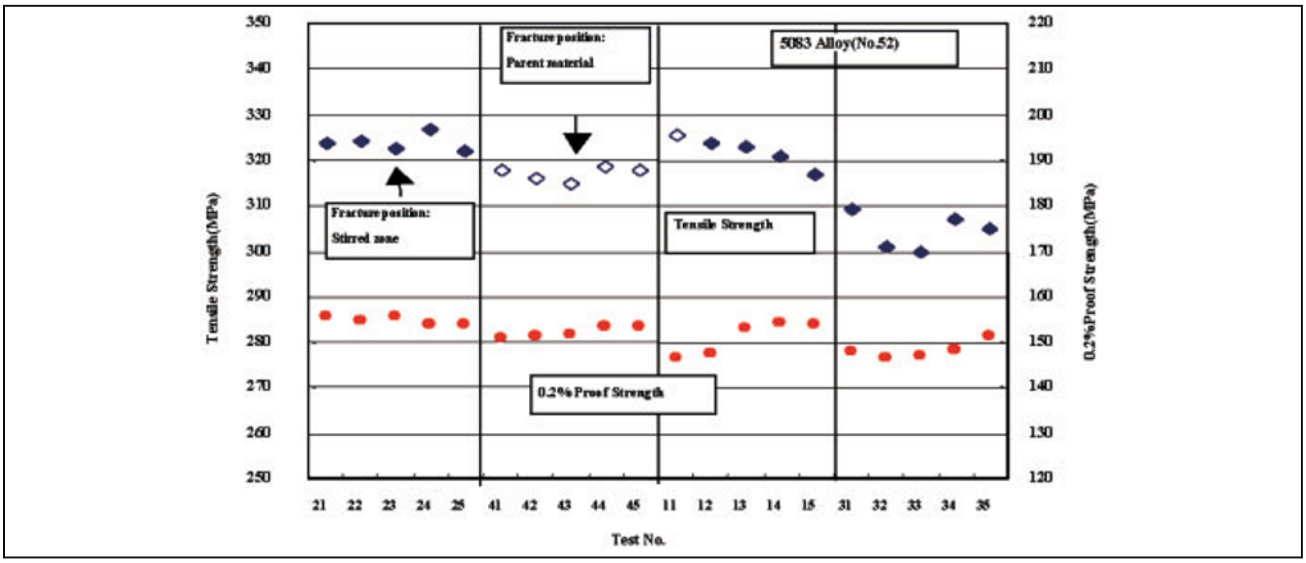

Figure 8 – Tensile properties of 52x joints

3.3.2 6xx joints

Figure 9 shows tensile properties of 61x joints, as typical results of 6xx joints.

Tensile strength and elongation varied from 215 to 255 MPa and from 11 to 8 % using a gage length of 50 mm according to the strength despite the result that all of the specimens fractured in HAZs. Such difference in the tensile strength seems to be caused by dissimilarities in FSW procedures and then to result from shapes of stirred zone shown in Figure 3 typically and their hardness distributions in Figure 7.

Elongation measured using a gage length of 50 mm was higher than that of 80 mm, and clearer difference between them was observed in comparison with that in 5xx joints. This tendency seems to depend on hardness distributions shown in Figure 7 and to result from localization of deformation in HAZ during tensile testing. However, such difference itself did not vary according to dissimilarities in FSW procedures.

Table 7 shows, for example, tensile properties of 61x joints.

The averaged joint efficiency of about 85 % was obtained in 6xx joints except in test specimens 6x3 with under-fill or undercut in their stirred zones. It seems to follow that the difference in strength in almost all of 6xx joints still represented dissimilarities in those of their parent materials even after FSW process.

3.3.3 7xx joints

In the case of 7xx joints, similar tensile and 0.2 % proof strengths were obtained despite difference in their fracture positions, that is, test specimens 711x and 712x fractured in stirred zones and others in parent materials. Difference by dissimilarities in FSW procedures was recognized in their elongation slightly.

Difference in elongation measured using a gage length of 50 mm and using that of 80 mm was less observed in comparison with that in 6xx joints, and this seems to depend on hardness distributions shown in Figure 6.

Table 8 shows, for example, tensile properties of 71x joints.

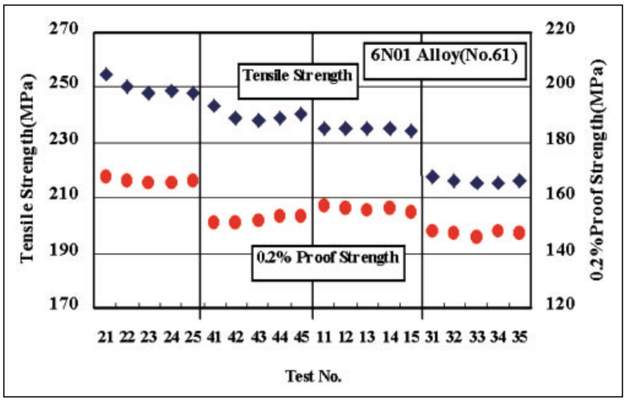

Figure 9 – Tensile properties of 61x joints

The joint efficiencies of about 97 % were obtained in both test specimens 71x and 72x and it became about 94 % in test specimens 73x. The total average of efficiency was calculated 96 % in 7xx joints. Similar result to that observed in 6xx joints seems to be obtained even in the strength of 7xx joints.

3.4 Bending properties

3.4.1 5xx joints

Figure 10 shows typical bent shapes of test specimen 524.

Their bent shapes were very uniform with smooth surfaces and no flaws and cracks on their surfaces were observed.

All 5xx specimens bent till the minimum former diameter of 12 mm (4 *t*) for both face and root sides. No difference caused by dissimilarities in parent materials or FSW procedures was observed in the bendability.

Moreover, these results do not seem to be affected by difference in hardness distributions in stirred zones shown in Figure 5.

3.4.2 6xx joints

Almost all 6xx test specimens bent till the minimum former diameter of 32 mm (10.7 *t*) for both face and root sides, but only in specimens 611, the diameter of 20 mm

Table 7– Tensile properties of 61x joints

		Tensile strength MPa	0.2 % proof strength MPa	Elongation %	Joint efficiency %
61	Average	242	159	5.6	84
	Standard	6.6	6.6	0.4	---
612	Average	250	166	5.4	87
	Standard	2.8	1	0.4	---
614	Average	240	152	5.8	83
	Standard	2	1.1	0.4	---
611	Average	235	156	5.4	82
	Standard	0.4	0.7	0.2	---
613	Average	216	147	6.7	75
	Standard	0.9	1	0.3	---

Table 8 – Tensile properties of 71x joints

		Tensile strength MPa	0.2 % proof strength MPa	Elongation %	Joint efficiency %
71	Average	423	311	9.2	98
	Standard	5	8.2	2.4	---
712	Average	424	303	9.1	99
	Standard	4.6	0.7	0.7	---
714	Average	423	315	11.5	98
	Standard	2.1	0.7	0.7	---
711	Average	421	318	6.5	98
	Standard	7.9	0.9	1.6	---
713	Average	399	300	7.2	93
	Standard	4.4	1	0.3	---

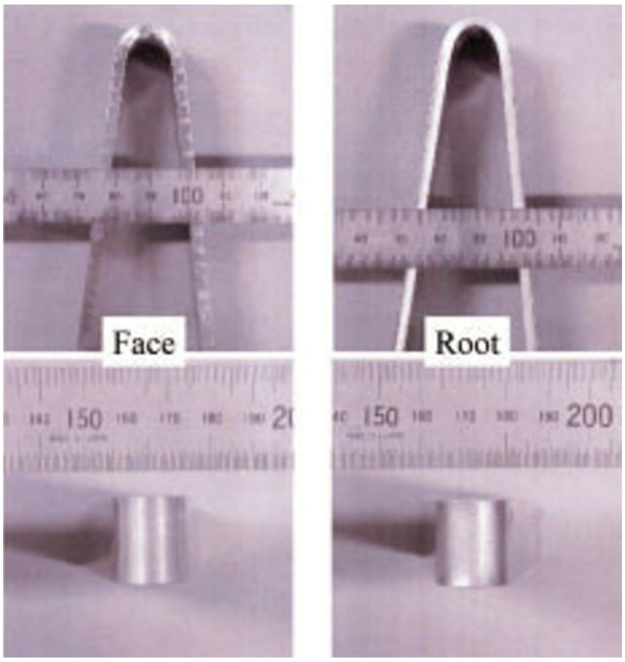

Figure 10 – Typical bent shapes of test specimen 524 for former diameter 12 mm (4t)

(6.7 *t*) was obtained for both sides. Although bent shape of specimen 611 was uniform, others were almost convex in the stirred zone in this testing. These results are shown in Figure 11, where symbol ▲ represents occurrences of flaws or cracks observed in their HAZs.

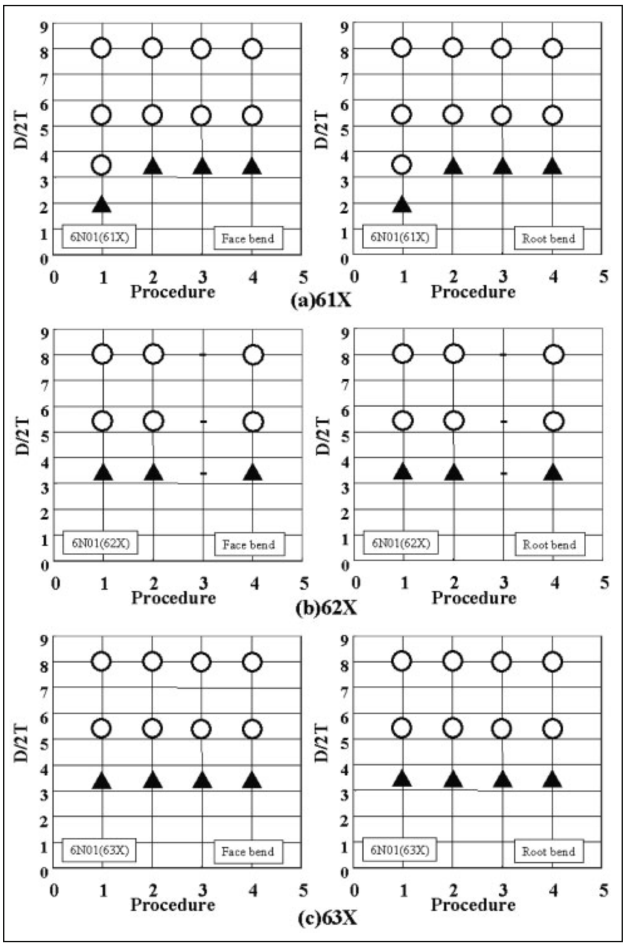

Figure 11 – Results of bend testing of 6xx joints

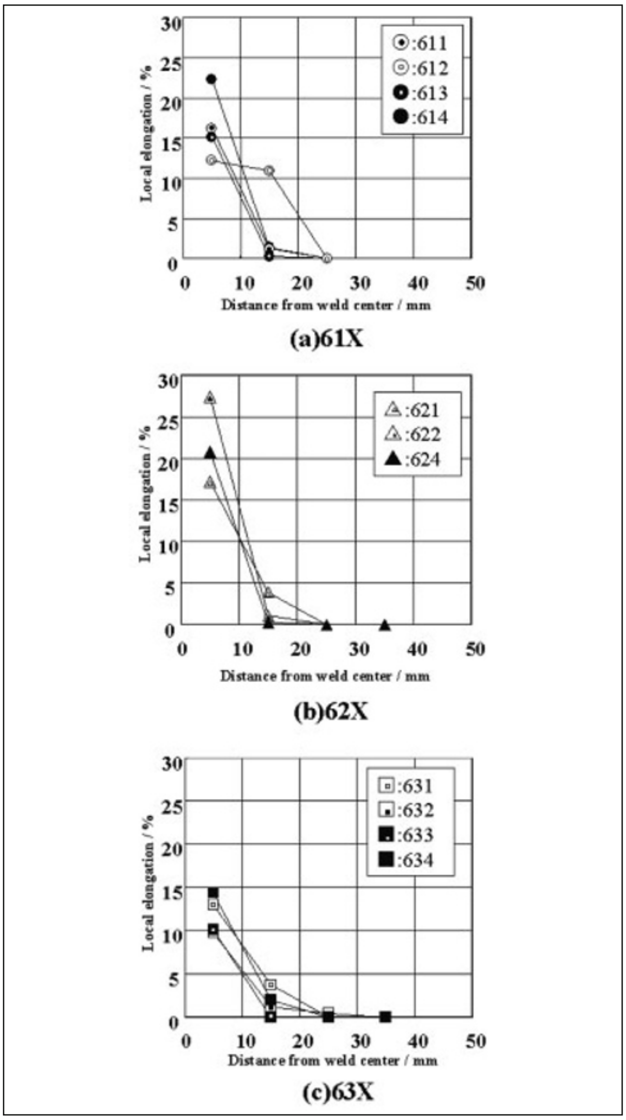

Figure 12 – Distribution of local elongation in tensile testing of 6xx joints

It proved that difference in bendability caused by dissimilarities in parent materials or FSW procedures was limitedly recognized.

Difference in their bendability was observed, in part, despite the same elongation in relationship between elongations of joints shown in 3.3.2 and former diameters for 61x joints. The bendability thus seemed not to depend on the elongation. Then, effect of distribution of local elongation at each joint was examined. Figure 12 shows distribution of local elongation obtained in the tensile testing.

The highest local elongation was observed at the centre of the stirred zone and this elongation remarkably decreased with the distance from the centre in almost all of the specimens, though only in specimen 611, the higher elongation was kept over comparatively wider range of the joint. Such distribution of local elongation is considered to result in rise of bendability in specimen 611.

3.4.3 7xx joints

Almost all of 7xx test specimens bent till the minimum former diameter of 20 mm (6.7 *t*) for both face and root sides, but only in the face side of specimen 713, the

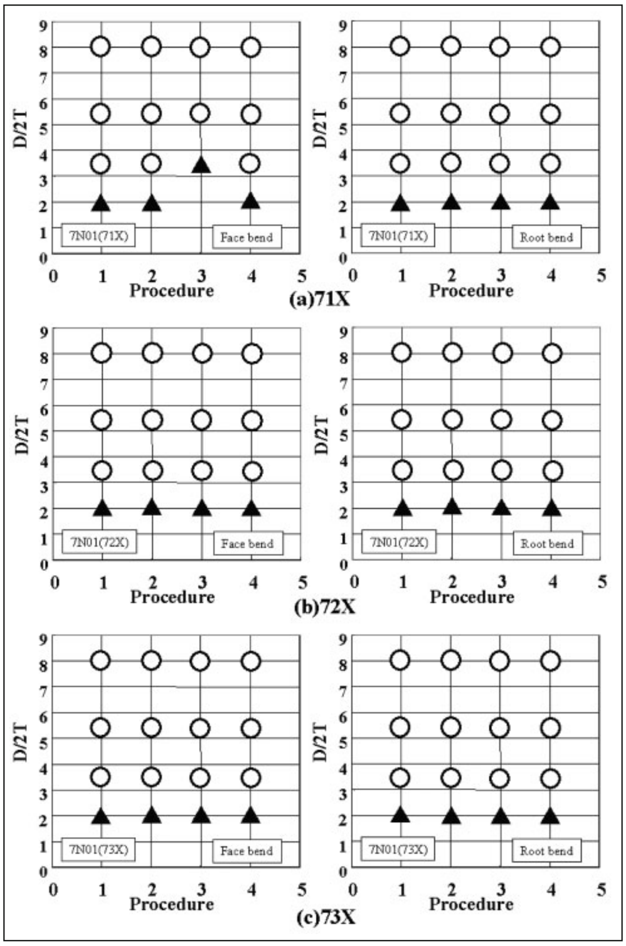

Figure 13 – Results of bend testing of 7xx joints

diameter was not less than 32 mm (10.7 *t*). The results are shown in Figure 13, where symbol ▲ also represents occurrences of flaws or cracks. These were observed almost at HAZs except in the face side of specimen 713, where they occurred at the toe of stirred zone.

It proved, thus, that the difference in bendability by dissimilarities in parent materials or FSW procedures was limitedly recognized too.

The effect of distribution of local elongation was examined similarly to that of 6xx joints. However, though behaviour of distribution of local elongation seemed to be fairly different mainly according to parent materials, any peculiar distribution was not considered to be observed in specimen 713. On the other hand, in this specimen, the stirred zone with under-fill or undercut was obtained as shown typically in Figure 3. Therefore, this shape of stirred zone seems to affect the bendability strongly.

Moreover, these results do not seem to be influenced by difference in hardness distributions in stirred zones shown in Figure 6.

4 CONCLUSIONS

1. In order to furnish as many fundamental and metallurgical factors as possible, shapes and structures of friction stir welded zone, and their hardness distribution, etc., were clarified, and these profiles were put in order according to parent materials and also FSW procedures. Some convenient means as a measure, from practical use, to estimate these profiles were examined though further research seemed to be needed for the establishment, together with theorization of FSW mechanism.

The dissimilarities in both of them were clearly reflected in the hardness distributions among features of friction stir welded zones studied, and the distributions to be considered as suitable were obtained under their specified combinations.

2. Tensile properties were clarified in joints under dissimilarities in both of them. These results seem to be such a valuable knowledge that any parallel case is scarcely caught sight of in the previous results and to form suitable information for backing-up on writing out draft standards.

In 5xx joints, the joint efficiency of about 100 % was obtained. Difference in these properties caused by dissimilarities in parent materials was hardly observed though difference by dissimilarities in FSW procedures was recognized clearly in their fracture positions and slightly in their elongations.

In 6xx joints, the joint efficiency of about 85 % was obtained except in some joint. It seems to follow that difference in the strength at almost all of 6xx joints still represented dissimilarities in those of their parent materials. Difference by dissimilarities in FSW procedures was recognized in the strength.

In 7xx joints, the averaged joint efficiency of about 96 % was obtained. Similar result to that observed in 6xx joints seems to be obtained even in the strength of 7xx joints. Difference by dissimilarities in FSW procedures was recognized likewise in those of 5xx joints.

3. Bending properties were clarified similarly to tensile properties.

All of 5xx joints bent till the minimum former diameter of 12 mm (4 *t*) for both face and root sides. Any difference caused by dissimilarities in parent materials or FSW procedures was not observed in the bendability.

Almost all of 6xx joints bent till 32 mm (10.7 *t*) for both face and root sides, but only in specimen 611, the diameter of 20 mm (6.7 *t*) was obtained for both sides. It is considered to result from distribution of higher local elongation kept over a comparatively wider range of the joint.

Almost all of 7xx joints bent till 20 mm (6.7 *t*) but only in the face side of specimen 713, the diameter was not less than 32 mm (10.7 *t*). It is considered to result from the shape of the stirred zone with a kind of under-fill or undercut.

Difference due to dissimilarities in parent materials or FSW procedures was limitedly recognized in the bendability of specified joints among 6xx and 7xx joints.

REFERENCE

[1] Russell M.J., Shercliff H.R.: Analytical modelling of friction stir welding, INALCO 98, 7th International Conference, 1998, 185-195.