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AN EVALUATION OF THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF SUBMERGED-ARC AND GAS-METAL-ARC WELDS IN HSLA-100 STEEL

by

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1.0 INTRODUCTION

The replacement of high strength HY quenched and tempered (Q&T) grades of steel by the more weldable HSLA low carbon grades in naval applications has resulted in research investigations to develop suitable welding consumables and procedures to meet the stringent weld metal property requirements. The program outlined in this report addresses the development and evaluation of consumables for joining high strength copper-precipitation strengthened HSLA 100 steel with a nominal yield strength of 690 MPa.

In Phase I of the program the objective was to evaluate commercially-available welding consumables and develop weld procedures for joining HSLA 100 steel using the submerged-arc (SAW) and gas-metal-arc (GMA) welding processes. The evaluation included a quantitative assessment of weld metal microstructure and measurement of weld metal mechanical properties. Phase II of the program will evaluate welding wire formulations that have been designed from the data of Phase I to provide optimum weld metal mechanical properties in the joining of HSLA 100 steel plate. Targeted properties are 700 MPa yield strength and Charpy impact resistance of 47 J at -50°C and 81 J at -20°C[1].

The results obtained in Phase I are given in this report. The Phase I program has two components. Initially, bead-in-groove (BIG) welds were deposited in HSLA 100 plate with a range of commercially-available consumables to provide a fundamental understanding of the effects of weld composition and energy input on the microstructure and resultant mechanical properties of as-deposited weld metal. Based upon the results of the BIG welds, full-thickness welds were prepared employing selected consumables and welding parameters to give optimum mechanical properties of the weld metal.

2.0 BEAD-IN-GROOVE WELDS

2.1 Experimental

Single-pass, submerged-arc (SA) BIG welds were deposited with energy inputs of 1, 2, 3 and 4 kJ/mm in 25 mm thick HSLA 100 steel plate. The plate composition is listed in Table 1. The size of the machined grooves (Fig. 1) was increased to accommodate the increase in energy input, while maintaining the same level of dilution from the base plate for each weld deposit. Figure 1 shows typical macrosections of the single-pass, submerged-arc welds. Three commercially-available wire/flux combinations were selected and are listed in Tables 2 and 3, along with the weld identification codes. The welding conditions and parameters are shown in Fig. 1. Semi-automatic pulsed-gas-metal-arc (P-GMA) bead-in-groove welds were made using two commercially-available electrodes (LTEC 120S1 and Thyssen S3 NiCrMo) with an external 80% Ar + 20% CO_2 shielding-gas mixture (C20) in the HSLA 100 steel (Table 4). The welds were made in the flat position with energy inputs of approximately 0.75, 1.0 and 2.0 kJ/mm. The welding conditions and parameters employed for the welds are shown in Table 5. To obtain an increase in energy input the welding travel speed was decreased and an oscillating weave technique was employed using a Gullco welding carriage. The size of the machined groove (Fig. 2) was increased to accommodate the increase in energy input.

Weld-metal tensile specimens, sections for metallography and chemical analysis were extracted from each weldment. The chemical compositions of the welds were determined by spectrographic analysis.

The microstructures of the BIG welds were characterized by optical metallography using standard preparation and etching techniques. Transmission electron microscopy, employing carbon extraction replicas was used to identify constituents in selected welds. Microhardness surveys were also conducted for each weld deposit. The fracture surfaces of Charpy specimens tested at -196°C were examined by SEM to determine cleavage facet dimensions and orientation.

2.2 *Results*

2.2.1 *Weld Composition*

The compositions of the SA welds are shown in Tables 6, 7 and 8. The nominal weld metal composition was not significantly different for the three wire/flux combinations. There was also no significant change in weld-metal chemistry with increasing energy input. The dilution of the weld from the base metal was calculated geometrically and ranged between 50 to 60% for the 1-4 kJ/mm energy inputs.

The chemical compositions of the GMA welds deposited in HSLA 100 are shown in Tables 9 and 10. In general, the chemical compositions resulted from alloy additions in the wire (Table 4), shielding gas and dilution with the base plate. For the two series of welds deposited in HSLA 100 higher Mn and Si and lower Ni and Cr levels were observed in the welds made with the Thyssen S3 NiCrMo wire compared with the welds made with the LTEC 120S1 wire. There was no significant change in chemistry, other than a decrease in Cu, with increasing energy input. The decrease in Cu with increasing energy input was attributed to a reduction in dilution from the base metal ranging from 40% at 0.75 kJ/mm to 24% at 2 kJ/mm energy input.

2.2.2 *Microstructure*

The microstructures of the SA bead in groove welds are shown in Figs. 3 to 10. The overall columnar structure is shown in low magnification (100x) micrographs, while the details of the microconstituents are revealed at the high magnification (500x). The corresponding hardnesses of the weld metal are listed in Table 11. The microstructure of the HSLA 100 welds, shown typically for the LTEC 120 S1 and OP121TT consumable combination in Figs. 3-6, ranged from low-carbon lath martensite with some bainite regions at the low 1 kJ/mm energy input to mainly coarse bainite at the highest energy input. There was very little indication of grain boundary ferrite in any of the weld deposits. The lath martensite microstructure was characterized by elongated packets, with the long axes of the packets running in more than one direction (Fig. 3). It was assumed, based upon the definition of martensitic features by Torronen[2], that a packet is the smallest unit surrounded by high-angle boundaries. Recent thin-foil work at MTL on high-strength weld metals with a similar lath martensite structure has indicated that the packet boundaries are high angled. Examination of carbon extraction replicas in the TEM revealed that the elongated packets in the 1 kJ/mm HSLA 100 weld metal, which were of the order of 2 to 4 μm wide with a length to width aspect ratio ranging from 3:1 to 10:1, were composed of a series of parallel laths (Fig. 11). These laths within a packet were likely separated by low angle boundaries.

The bainitic microstructure particularly at the highest energy input of 4 kJ/mm was a coarser structure than the lath martensite with a lower aspect ratio for individual packets (Fig. 6). The bainitic packets, as revealed by extraction replicas in the TEM are shown in Fig. 12. Packets were 8 to 10 μm wide at 4 kJ/mm.

SEM fractographic examination of fractured Charpy specimens revealed further evidence about the microstructural units associated with the fracture of the SA bead-in-groove welds. The cleavage facet size and orientation determined from the fracture surface of the LTEC 120 S1 bead-in-groove 1 kJ/mm weld (Fig. 13a) were similar to the lath martensite packet orientation and dimensions, i.e. 2 to 4 μm. The much coarser, less elongated cleavage facets (Fig. 13b) observed in the 4 kJ/mm weld corresponded in shape and size to the bainite packets (Figs. 6 and 12).

The weld-metal microstructure of the GMA welds deposited with the LTEC 120 S1 wire and C20 shielding gas in HSLA 100 steel are shown in Figs. 14-16. At an energy input of 0.75 kJ/mm the deposited weld metal consisted of relatively narrow elongated columnar grains ranging in width from 50 to 75 μm. With increasing energy input the columnar structure was less well defined and the grain boundaries were more discontinuous. The primary microstructural features at the 0.75 kJ/mm and 1.0 kJ/mm energy inputs consisted of lath martensite with some bainite and limited amounts of discontinuous grain boundary ferrite. The relatively high hardness of 320 Hv (Table 12) confirmed that martensite was present. At 2.0 kJ/mm there was a slight coarsening of the microstructure and a corresponding decrease in hardness (286 Hv). The structure consisted of a mixture of martensite and bainite.

2.2.3 *Mechanical Properties*

The results of the tensile tests of the HSLA 100 SA bead-in-groove welds deposited with the three wire/flux combinations are shown in Table 13. For each of the three series of welds there was a decrease in yield strength with increasing energy input. The tensile results indicate that for the bead-in-groove welding conditions the required yield strength (700 MPa) can be met at energy inputs ≤4 kJ/mm for the LTEC 120/OP121TT consumable combination and at ≤3 kJ/mm for the other two consumable combinations. The results also suggest that a weld procedure employing a multipass technique and hence lower dilution may have marginal strength, unless the reheated regions contribute an increment of strength along with the as-deposited regions. Previous research suggests that this is unlikely and therefore the weld-metal strength of multipass construction welds may be too low using the existing consumable combinations.

The weld-metal tensile results for the GMA bead-in-groove welds are shown in Table 14. The data are limited to the welds deposited at 1 and 2 kJ/mm since there was not sufficient cross-sectional area in the lowest energy input welds to extract tensile specimens. The minimum yield strength requirement of 700 MPa was met or exceeded for all welds. In general, there was no significant difference in tensile properties between the series of welds made with either the LTEC 120S1 or the Thyssen S3 NiCrMo wires. There was a general decrease in yield strength with increasing energy input.

Sub-size Charpy specimens were taken from the Series A, SA, bead-in-groove welds to determine the relative notch toughness as a function of energy input and test temperature. As shown in Table 15 there was a slight decrease in toughness with increasing energy input only at test temperatures ≤-50°C.

3.0 FULL THICKNESS WELDS

3.1 *Experimental*

Full thickness (25 mm) SA and GMA welds were made in HSLA 100 steel at a nominal energy input of 2 kJ/mm. Welding consumables and weld process operating parameters are listed in Table 16. The weld preparation is shown in Fig. 17. The measured data from these welds will serve as the bench mark in the future development of consumable chemistries. The microstructure was fully characterized by optical microscopy and hardness surveys. Mechanical testing included tensile, Charpy impact and dynamic tear testing of the weld metal.

3.2 Results

3.2.1 Weld Composition

The root region compositions of the SA and GMA full-thickness welds are listed in Table 17. The compositions reflected the contributions from the welding wire, flux, shielding-gas composition and dilution from the base metal. The base-metal dilution in the root region was of the order of 25% for the SA weld and 14% for the GMA weld. The higher carbon content in the GMA weld is from the CO_2 in the shielding-gas mixture. Lower copper in the GMA weld resulted from lower dilution from the base metal.

3.2.2 Microstructure

The microstructure of the multi-pass full thickness SA weld was composed of as-deposited (75%) and reheated regions (25%). The as-deposited microstructure shown in Fig. 18 was primarily bainite with some lath martensite and occasional discontinuous grain boundary ferrite. It should be noted that it was difficult to distinguish the columnar grains because of the lack of ferrite veins delineating the columnar boundaries. The microstructure of the reheated region was similar to the as-deposited region i.e. mainly bainite (Fig. 19). In the portion of the reheated region where the reheat temperature was near AC_1, carbides have formed (Fig. 19b) along the prior austenite boundaries corresponding to the original as-deposited columnar grains. The hardness of the as-deposited and reheated regions was similar i.e., 282 VHN.
The GMA full-thickness weld had a slightly higher proportion (35%) of reheated structure as a result of the weld pass sequence used. The as-deposited microstructure contained a mixture of fine bainite and lath martensite as shown in Fig. 20 with a hardness of 310 VHN. Because the bainitic reheated microstructure (Fig. 21) was so similar to the as-deposited one it was difficult to distinguish between the two regions. The tempered portion of the reheated region shown in Fig. 21b contained carbides forming along prior austenite boundaries. The hardness of the reheated region was 315 VHN.

3.2.2 *Mechanical Properties*

The tensile properties of both the GMA and SA full-thickness welds exceeded the yield strength requirement of 700 MPa as indicated in Table 18. As shown in Table 19, the Charpy impact resistance of the GMA weld at -50°C (46 J) was borderline with respect to the 47 J requirement. At -20°C the weld did not meet the required level of 81 J. For the SA weld, the results in Table 19 indicate that the required toughness level was met at both the -50°C and -20°C test temperatures. It should be noted that the tensile and Charpy specimens were taken from the root region of the welds.

4.0 DISCUSSION

4.1 *HSLA 100 Weld Metals*

The experimental program in Phase 1 has provided a quantitative assessment of weld-metal microstructure and its relationship with mechanical properties in welds prepared in HSLA 100 using selected, commercially-available welding consumables. The work on bead-in-groove welds was designed to evaluate the structure/property relationships in as-deposited weld metal while presenting the worst case situation of maximum dilution from the base metal, i.e. the root region of a weldment. Of three selected wire/flux combinations, the LTEC 120 S1 wire/OP121TT flux gave the most consistent yield strength values (exceeding 700 MPa) over the energy input range of 1-3 kJ/mm. Limited data from subsize Charpy test specimens in the 2 kJ/mm welds indicated that the notch toughness property requirements would likely be met in full-size test specimens taken from full-thickness welds. Specifically, the microstructure of the LTEC 120 S1/OP121TT BIG weld contained lath martensite (1 kJ/mm) or mixed bainite/martensite (2-4 kJ/mm) components with a fine packet size which contributed to the observed high strength and toughness properties. It should be noted that despite the dilution from the base metal of 50-60 per cent, the BIG SA weld metal composition did not result in a microstructure deleterious to mechanical properties. Such was not the case for the HY 100 BIG weld metals and will be discussed later in the comparison of HSLA 100 and HY 100 weld properties.

The results of the BIG GMA welds were similar to the SA welds in terms of microstructure and mechanical properties. However, there was some concern that the yield strength of the BIG weld deposited at 2 kJ/mm was less than required and that there might be a problem in achieving a yield strength of 700 MPa in full-thickness welds with less dilution expected from the base metal and the presence of reheated weld microstructure.

The full-thickness SA weld prepared with the LTEC 120 S1/OP121TT welding consumables exceeded both the strength and toughness requirements. A fine bainite/lath martensite weld-metal microstructure was responsible for attaining these properties. The reheated region of the weld, with hardness comparable to the as-deposited region, contributed to the weld-metal strength. This strength contribution from the reheated region was attributed, in part, to the formation of fine copper precipitate particles. Observations of copper precipitation in reheated HSLA 80 weld metal have been reported by the authors(3).

The GMA full-thickness weld did not reach the required toughness level (Table 19). Based on the marginal BIG weld tensile property results no preheat was used in order to produce a faster cooling rate. This, combined with the higher level of C (0.077) in the weld has resulted in a bainite/martensite microstructure with a hardness of 310 VHN in the as-deposited and 315 VHN in the reheated regions. This microstructure, while contributing to a high yield strength (805 MPa) was too brittle for acceptable resistance to brittle fracture. The carbon content of the weld depended on contributions from the wire, CO_2 the the shielding gas, and dilution from the base metal.

4.2 Comparison of HSLA 100 and HY 100 Weldments

It is appropriate to compare the mechanical properties of the HSLA 100 weld metals with those of HY 100 welds. The comparison was made for both bead-in-groove and full-thickness welds which had been prepared using the same welding process (SA), welding consumables (LTEC 120 S1 wire, OP121TT flux) and weld-process operating conditions.

For the BIG welds, the variations in hardness, yield strength and Charpy impact energy as a function of energy input are shown in Figs. 22, 23 and 24. The HY 100 weld metals had significantly higher levels of strength and hardness than the

HSLA 100 weld metals. Hard, lath martensite at energy inputs up to 3 kJ/mm was responsible for the high strength and hardness of the HY 100 BIG welds. In the HSLA 100 welds, martensite observed in the 1 kJ/mm weld, was replaced by bainite at higher energy inputs. The greater tendency to form a hard, martensitic microstructure in the HY 100 BIG welds was attributed to the higher hardenability, in particular the higher carbon content, in the HY 100 weld metal. Table 20 contains a summary of the compositions of the HSLA 100 and HY 100 weld metals. The dilution (~50%) from the base metal was responsible for the hardenability exhibited by the HY 100 BIG weld. As shown in Fig. 24 the hard martensitic structure of HY 100 weld metals resulted in much poorer toughness than the HSLA 100 BIG welds.

For the full thickness SA welds, Table 21 shows that the HSLA 100 and HY 100 welds exceeded the targeted levels for yield strength and notch toughness. The hardness of the HY 100 weld was 304 VHN compared with 282 VHN for the HSLA 100 weld. The microstructures of the HSLA 100 and HY 100 weld metals were similar i.e., fine bainite with some lath martensite. Lower dilution (~25%) with the base metal in the full-thickness welds resulted in lower carbon content in the HY 100 welds (compared to BIG HY 100 welds).

4.3 *Selection of Wire Composition for Phase II Program*

A review of the published literature (Table 22) indicates that, in general for weld metal at the 700 MPa strength level, the mechanical properties have been correlated with chemical composition rather than microstructure[4-11]. From these reports, some general conclusions can be drawn regarding the effect of certain alloying additions:

1. Small additions of carbon increase hardenability, tensile strength, and hardness significantly while decreasing notch toughness. Susceptibility to hydrogen cracking and solidification cracking increases as the carbon level increases. Most authors[4] recommend limiting the carbon content to a maximum of 0.10 to 0.12%.

2. Manganese increases hardenability, tensile strength and hardness. The effect of manganese on toughness is less clear. Most of the evidence[4] suggests that manganese improves or has a less deleterious effect on

notch toughness that other strengthening additions. Heuschkel[8] reported that manganese lowered notch toughness. Dorschu and Lesnewich[9] presented data showing a general trend to decreasing impact energy with increasing manganese content. For HY 100 consumables, the current practice is to have a manganese content in the range of 1.4 to 1.6%[5].

3. Nickel only moderately increases hardenability, tensile strength, and hardness but increases toughness significantly. The susceptibility to solidification cracks increases as the nickel content increases, and an upper limit of 2.5%[4,6] or 2.0%[5,7] is recommended.

4. Chromium increases tensile strength and hardness, but reduces impact toughness significantly. The consensus is that chromium should be limited to the minimum necessary to achieve a 700 MPa yield strength. The optimum recommended level is 0.3%.

5. Molybdenum also increases hardenability, tensile strength and hardness. Molybdenum additions up to a certain level improve impact toughness. Shackleton[4] reported that above 0.5% Mo, impact toughness was reduced sharply. Heuschkel[8] reported that up to 2.0% Mo was beneficial. Based on this evidence, additions of molybdenum above 0.5% may be beneficial.

6. The effect of titanium on 700 MPa yield strength weld metal is unclear. In lower strength weld metals, titanium additions are known to improve the properties by increasing the proportion of acicular ferrite via inclusion modification. In martensitic/bainitic microstructures, this mechanism is not operative. Dorschu and Lesnewich[11] reported that additions of 0.008 to 0.020% Ti in a low carbon (0.08% C) 960 MPa weld metal improved notch toughness significantly. Heuschkel[8] reported that titanium reduced impact toughness and the best properties were obtained with no titanium additions.

7. Copper increases tensile strength and hardness. Copper levels up to 0.6% Cu can either improve toughness or have a negligible effect.

8. Silicon is necessary for deoxidation and weld pool fluidity, but should be limited to a maximum of 0.30% Si. Vanadium and niobium sharply reduce notch toughness.

The results of Phase I show that the weld-metal compositions produced using the LTEC 120 S1 wire were within the recommended limits. The full-thickness submerged-arc welds demonstrated that adequate properties could be obtained with the LTEC 120 S1 wire, but the toughness could be improved by controlled additions of alloying elements (Mo initially; possibly Mn, Ti) which would refine the microstructure while avoiding the detrimental effects of solid-solution strengthening and increased amounts of secondary (M-A) phase.

The results obtained with the full-thickness gas-metal-arc welds using the LTEC 120 S1 wire suggest that the carbon level of the weld-metal deposit should be reduced from the present level of 0.08% C to the level of the full-thickness submerged-arc weld (0.05% C) to obtain tensile and toughness properties similar to the submerged-arc welds.

Metal-cored wires are the most cost-effective method for screening proposed chemical compositions. Once a reasonable composition has been identified, a solid wire can be produced. While recent consumable development efforts for joining high-strength steels by the US Navy and consumable manufacturers have been aimed at metal-cored and flux-cored wires, it is felt that ultimately solid electrode wires will result in the best and most consistent weld-metal properties.

SUMMARY AND RECOMMENDATIONS

Bead-in-groove (BIG) welds, deposited in HSLA 100 steel using the SA and GMA welding processes and three commercially available welding consumables were evaluated in terms of the effects of weld composition and energy input on the weld microstructure and resultant mechanical properties. A low carbon lath martensite formed at the lowest energy input (1 kJ/mm) and changed to a fine bainitic structure at the highest energy input (4 kJ/mm). For the SA welds acceptable yield strength (>700 MPa) and toughness were observed over the energy input range of 1-3 kJ/mm for one commercially available consumable and 1-2 kJ/mm for the other two consumables. For the GMA welds the minimum yield strength requirement of 700 MPa was met for the 1 kJ/mm weld. It was determined that low C (0.04-0.05) in particular and low Cr (0.5) levels in the HSLA 100 weld metals were important compositional factors leading to the attainment of the required weld properties. By comparison the HY 100 welds, containing the same principal alloying elements (C, Ni, Cr and Mo) but higher levels of C (0.12) and Cr (1.0%) had a much harder lath martensite microstructure which resulted in high yield strength but unacceptable notch toughness.

Full-thickness SA welds, prepared at a nominal energy input of 2 kJ/mm in HSLA 100 steel and with a C level of 0.049%, contained a fine bainitic/lath martensite microstructure in the as-deposited and reheated regions and exhibited adequate (>700 MPa) strength and toughness (>47 J at -50°C). The full-thickness GMA weld with a higher level of C (0.077%) had higher strength and hardness but borderline notch toughness properties.

It is recommended that the following scope of work be carried out in Phase II of the program:

1. Experimental metal-cored wires will be prepared with varying levels of C and Mo. The amounts of Mn, Si, Cr, and Ni will be fixed.

2. The welding wire formulations will be evaluated in terms of their ability to meet weld-metal mechanical property requirements. Bead-in-groove weld deposits will be prepared.

3. Those consumables which meet or exceed the mechanical property requirements will be used to produce full-thickness welds.

4. The strength and toughness of the full-thickness welds will be evaluated and related to weld composition and microstructure.

REFERENCES

1. U.S. Dept. of Defence, Military Standard MIL-E-23765/2C (SH), June 1983.
2. Torronen, K., Microstructural parameters and yielding in a quenched and tempered Cr-Mo-V steel, Tech. Res. Centre Finland Publ. 1979.
3. Smith, N.J., McGrath, J.T., Gianetto, J.A., and Orr, R.F., 1989. Microstructure/Mechanical property relationships of submerged-arc welds in HSLA 80 steel. Welding J. 68(3), 112S-120S.
4. Shackleton, D.N., 1973, Welding HY 100 and HY 130 steels. A Literature Review. The Welding Institute, Abington: Cambridge.
5. Grobe-Wordemann, J., Dittrich, S., 1987. SAW of HY 100 using high deposition rates along with an extra low hydrogen flux. Thyssen Draht Ag. Technical literature.
6. Machado, I.G., 1984. Weldability aspects of high yield strength Q&T steels. Ph.D. Thesis. Cranfield Institute of Technology.
7. National Materials Advisory Board. 1983. Effective use of weld metal yield strength for HY-steels. NMAB-380 National Academy Press. Washington, D.C.
8. Heuschkel, J., 1973. Weld metal property selection and control. Welding Journal 52(1): 15S-255S.
9. Dorschu, K.E., Lesnewich, A., 1964. Development of a filler metal for a high-toughness alloy plate steel with a minimum yield strength of 140 ksi. Welding Journal 43(12): 564S-576S.
10. Lyttle, J.E., Dorschu, K.D., Fragetta, V.S., 1969. Some metallurgical characteristics of tough high strength welds. Welding Journal 48(11): 493S-498S.
11. Boli, C., Yunhong, Z., 1988. Effects of manganese and nickel on toughness and strength of high strength steel submerged-arc weld metal of yield strength 550-800 MPa. IIW. Doc. II-1114-88.

Table 1 Chemical composition of high-strength steels.

	Element wt%											
Base Metal	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Nb	CE	Pcm
HY 100	0.17	0.33	0.23	0.008	0.010	2.62	1.52	0.48	0.04	0.012	0.80	0.34
HSLA 100	0.05	1.00	0.34	0.003	0.009	1.77	0.61	0.51	1.23	0.037	0.64	0.27

Note: Plate thickness - 25 mm

HSLA 100 was supplied by Luken U.S.A.

CE = C + Mn/6 + (Cu+Ni)/15 + (Cr+Mo+V)/5

Pcm = C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + Mo/15 + V/10 + 5(B)

Table 2 Chemical composition of SA welding electrode wires.

	Element wt%								
Electrode Wire	C	Mn	Si	S	P	Ni	Cr	Mo	Al
LTEC 120 S1	0.06	1.58	0.35	0.006	0.011	2.36	0.29	0.53	0.02
KOBE (LTEC 133)	0.11	1.92	0.13	0.008	0.009	2.63	0.05	0.72	----
Thyssen S3 NiMoCr	0.12	1.70	0.14	0.003	0.010	1.70	0.31	0.64	----

Note: Electrode wire diameters were 2.4 mm except LTEC 133 = 3.2 mm.

Table 3 Welding consumables and identification codes for SA welds.

Series	Weld No.	Energy Input kJ/mm	Consumables Wire/Flux
A	HSA-1	1	
	HSA-2	2	LTEC 120S1/
	HSA-3	3	Oerlikon OP121TT*
	HSA-4	4	
B	HSB-1	1	
	HSB-2	2	KOBE (LTEC133)/
	HSB-3	3	LTEC 633*
	HSB-4	4	
C	HSC-1	1	
	HSC-2	2	THYSSEN
	HSC-3	3	S3 Ni Mo Cr/
	HSC-4	4	UV421TT-LH*

* Highly basic flux.

Table 4 Chemical composition of GMA welding electrode wires.

	Element wt%								
Electrode Wire	C	Mn	Si	S	P	Ni	Cr	Mo	Al
LTEC 120 S1	0.06	1.58	0.35	0.006	0.011	2.36	0.29	0.53	0.02
Thyssen S3 NiMoCr	0.10	1.70	0.50	0.010	0.010	1.45	0.20	0.50	----

Note: Electrode wire diameters were 1.2 mm.

Table 5 GMA welding parameters for HSLA 100 BIG weldments.

Energy Input (kJ/mm)	Current (A)	Voltage (V)	Travel Speed (mm/s)
0.75	150	27	6.0
1.0	150	27	4.0
2.0	150	27	2.0

Note: 1. Electrical Extension = ~15 mm
2. Preheat Temperature = 93°C
3. Interpass Temperature = 149°C

Table 6 Chemical composition of submerged-arc BIG weld metals deposited in HSLA 100 steel using the LTEC 120 S1/OP121TT wire/flux combination (A).

Element wt%									
Weld No.	C	Mn	Si	S	P	Ni	Cr	Mo	Cu
HSA-1	0.04	1.2	0.38	0.006	0.010	1.7	0.50	0.51	0.67
HSA-2	0.04	1.2	0.36	0.005	0.010	1.8	0.50	0.51	0.65
HSA-3	0.04	1.2	0.37	0.005	0.011	1.8	0.50	0.50	0.64
HSA-4	0.04	1.2	0.38	0.006	0.010	1.8	0.50	0.50	0.62

Note: Al = 0.025, Nb = 0.026

Table 7 Chemical composition of submerged-arc BIG weld metals deposited in HSLA 100 steel using the KOBE wire/flux combination (B).

Element wt%									
Weld No	C	Mn	Si	S	P	Ni	Cr	Mo	Cu
HSB-1	0.04	1.1	0.35	0.004	0.008	1.8	0.46	0.60	0.69
HSB-2	0.04	1.1	0.38	0.004	0.008	1.8	0.46	0.60	0.66
HSB-3	0.04	1.2	0.36	0.004	0.008	1.8	0.41	0.63	0.59
HSB-4	0.04	1.2	0.36	0.004	0.008	1.8	0.43	0.60	0.64

Note: Al = 0.016, Nb = 0.024

Table 8 Chemical composition of submerged-arc BIG weld metals deposited in HSLA 100 steel using the THYSSEN wire/flux combination (C).

Element wt%									
Weld No	C	Mn	Si	S	P	Ni	Cr	Mo	Cu
HSC-1	0.05	1.2	0.30	0.005	0.008	1.8	0.50	0.53	0.72
HSC-2	0.05	1.2	0.28	0.005	0.008	1.8	0.50	0.55	0.71
HSC-3	0.05	1.3	0.28	0.005	0.010	1.9	0.50	0.54	0.68
HSC-4	0.05	1.3	0.26	0.005	0.010	1.8	0.51	0.55	0.68

Note: Al = 0.02, Nb = 0.023

Table 9 Chemical composition of GMA bead-in-groove weld metals deposited in HSLA 100 steel using the LTEC 120 S1 wire with a C20 shielding gas mixture.

Element wt%									
Weld No	C	Mn	Si	S	P	Ni	Cr	Mo	Cu
GSA-1	0.06	1.2	0.28	0.008	0.011	1.9	0.50	0.49	0.51
GSA-2	0.06	1.2	0.28	0.008	0.012	2.0	0.50	0.49	0.44
GSA-3	0.07	1.3	0.25	0.009	0.012	2.0	0.50	0.49	0.29

Note: Al = 0.010, Nb <0.020

Table 10 Chemical composition of GMA bead-in-groove weld metals deposited in HSLA 100 steel using the Thyssen wire with a C20 shielding gas mixture.

Element wt%									
Weld No	C	Mn	Si	S	P	Ni	Cr	Mo	Cu
GSB-1	0.07	1.29	0.45	0.006	0.007	1.64	0.39	0.49	0.48
GSB-2	0.07	1.30	0.47	0.007	0.008	1.8	0.36	0.49	0.41
GSB-3	0.07	1.37	0.49	0.007	0.007	1.50	0.32	0.50	0.30

Note: Al = 0.015, Nb < 0.015

Table 11 Microhardness measurements of SA bead-in-groove welds deposited in HSLA 100 steel.

Series	Energy Input (kJ/mm)	Microhardness DPH 500 g Load
A	1	317-338 (328)
	2	282-288 (285)
	3	277-290 (281)
	4	267-276 (273)
B	1	311-324 (316)
	4	260-275 (267)
C	1	326-337 (333)
	4	276-293 (285)

Note: (Avg.)

Table 12 Microhardness measurements of GMA bead-in-groove welds deposited in HSLA 100 steel.

Weld No.	Energy Input (kJ/mm)	Microhardness DPH 500 g. Load
GSA-1	0.75	312-328 (320)
GSA-2	1.0	311-339 (322)
GSA-3	2.0	283-290 (286)

Table 13 Tensile properties of submerged-arc weld metals deposited in HSLA 100 steel.

Weld No.	Energy Input (kJ/mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)	Reduction in Area (%)
HSA-1	1	871	1014	19	65
HSA-2	2	729	892	23	68
HSA-3	3	712	853	23	68
HSA-4	4	679	844	24	67
HSB-1	1	834	974	20	61
HSB-2	2	727	842	20	62
HSB-3	3	686	843	23	65
HSB-4	4	649	823	24	65
HSC-1	1	867	1001	20	66
HSC-2	2	733	885	22	63
HSC-3	3	687	847	23	62
HSC-4	4	658	839	25	69

Table 14 Tensile properties of GMA BIG weld metals deposited in HSLA 100 steel.

Weld No.	Energy Input (kJ/mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)	Reduction in Area (%)
GSA-2	1.0	794	992	21	60
GSA-3	2.0	666	867	24	63
GSB-2	1.0	793	966	21	62
GSB-4	2.0	666	865	25	62

Table 15 Sub-size Charpy impact data for SA bead-in-groove welds deposited in HSLA 100 steel with LTEC 120 S1/OP121TT welding consumables.

	Impact Energy J			
Weld No.	-80°C	-50°C	-20°C	20°C
HSA-2	33	60	61	63
HSA-3	23	58	63	65
HSA-4	27	42	62	62

Table 16 Welding procedure for the full thickness SA and GMA welds.

Weld Process	Energy Input (kJ/mm)	Current (A)	Voltage (V)	Travel speed (mm/s)	Preheat Temp.°C
SA	2.0	470	32	7.8	90
GMA	1.5	160	26	3.0	25

Note: SA consumables 2.38 mm LTEC 120 S1 wire, OP121TT flux
GMA consumables 1.14 mm LTEC 120 S1 wire, 80 Ar + 20 CO_2 gas.

Table 17 Composition of full thickness welds.

Weld	C	Mn	Si	S	P	Ni	Cr	Mo	Cu
GMA	0.077	1.3	0.29	0.009	0.012	2.2	0.40	0.49	0.17
SA	0.049	1.3	0.44	0.007	0.016	2.1	0.43	0.48	0.31

Table 18 Tensile properties of full thickness SA and GMA welds.

Weld	Yield Strength MPa	Ultimate Strength MPa	Elongation %	Reduction Area %
GMA	805	986	23	63
SA	725	889	23	70

Table 19 Charpy impact energy for full thickness SA and GMA welds.

Impact Energy, J				
Weld	-80°C	-50°C	-20°C	20°C
GMA	18, 31	46, 49, 42	69, 70	80, 79
SA	17, 43	61, 64, 58	94, 92	124, 122

Table 20 Compositions of HY 100 and HSLA 100 SA weld metals.

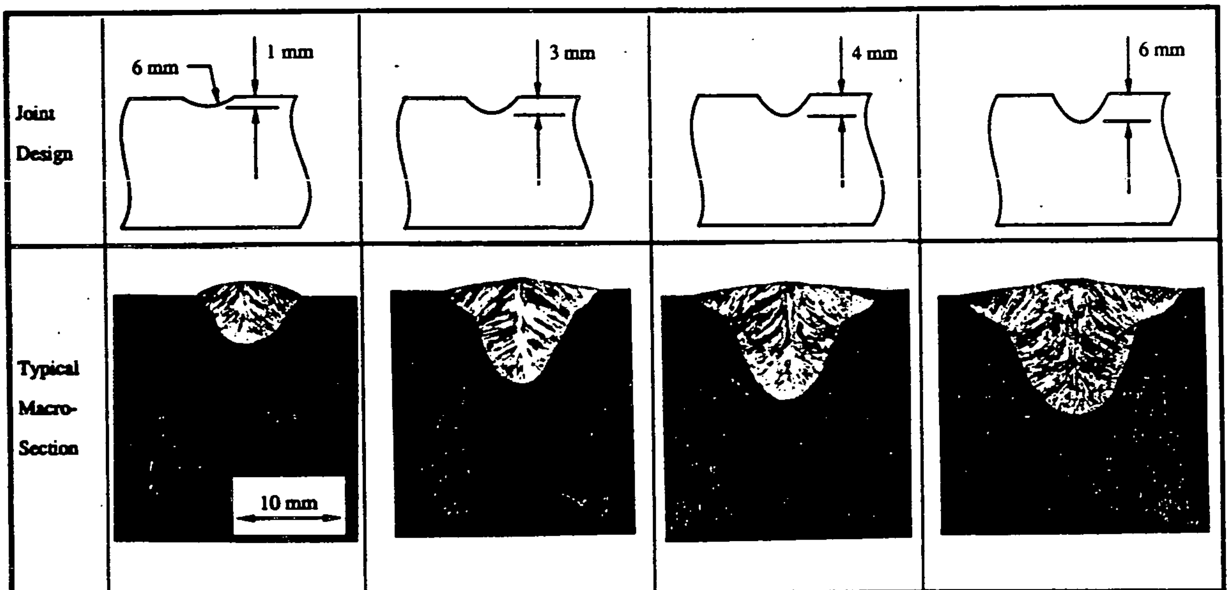
Weld	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	C.E.
BIG HSLA 100	0.04	1.2	0.36	0.005	0.010	1.8	0.50	0.51	0.65	0.60
F.T. HSLA 100	0.049	1.3	0.44	0.007	0.016	2.1	0.43	0.48	0.31	0.61
BIG HY 100	0.12	0.72	0.30	0.008	0.014	2.3	1.0	0.47	0.02	0.68
F.T. HY 100	0.08	1.15	0.37	0.005	0.015	2.5	0.67	0.48	0.02	0.67

Table 21 Mechanical properties of full thickness HSLA 100 and HY 100 SA weld metals.

Weld	Hardness VHN	Ultimate Strength MPa	Yield Strength MPa	Charpy Impact, J -50°C	-20°C
HY 100	304	902	816	62	92
HSLA 100	282	889	725	61	93

Table 22 Recommendations in published literature on various compositional limits

Reference	Element	Recommended Range %
Howden et al [7]	C	only enough for strength
	Mn	2.2
	Ni	<2.0
	Cr	only enough for strength
	Mo	only enough for strength
	Ti	beneficial
Grobe-Wordemann and Dittrich [5]	C	<.10 (solid cracking)
	Mn	1.4 to 1.6
	Ni	<2.0 (solid cracking)
	V, Nb	ALAP
McHado [6]	C	ALAP (solid cracking)
	Ni	<2.5 (solid cracking)
Boli and Yunhong [11]	C	<.10
	Mn	1.5 to 1.9
	Ni	1.3 to 1.7 (Ni + Mn = 3.2 to 3.6)
	Cr	<.20
	Cu	<.20
Heuschkel [8]	C	<.12
	Mn	ALAP
	Ni	<4.5
	Cr	<1.0
	Mo	2.0 optimum
	Ti	not good
	Cu	1.0 to 1.5 (increased toughness
	Co	beneficial (increased strength and toughness)
Shackleton [4]	C	.04 - .12
	Mn	beneficial (increased toughness)
	Ni	<2.5
	Cr	ALAP
	Mo	<.50
	Ti	beneficial
	Cu	<.60



Energy Input kJ/mm	1	2	3	4
Current A	400	450	500	570
Travel Speed mm/s	12.5	7.8	5.9	5.1

Note; Voltage = 35 V, Electrical Extention = 32 mm, Preheat Temperature = 93°C

Fig. 1. Joint design preparation, macrosections and operating parameters for submerged-arc bead-in groove welds.

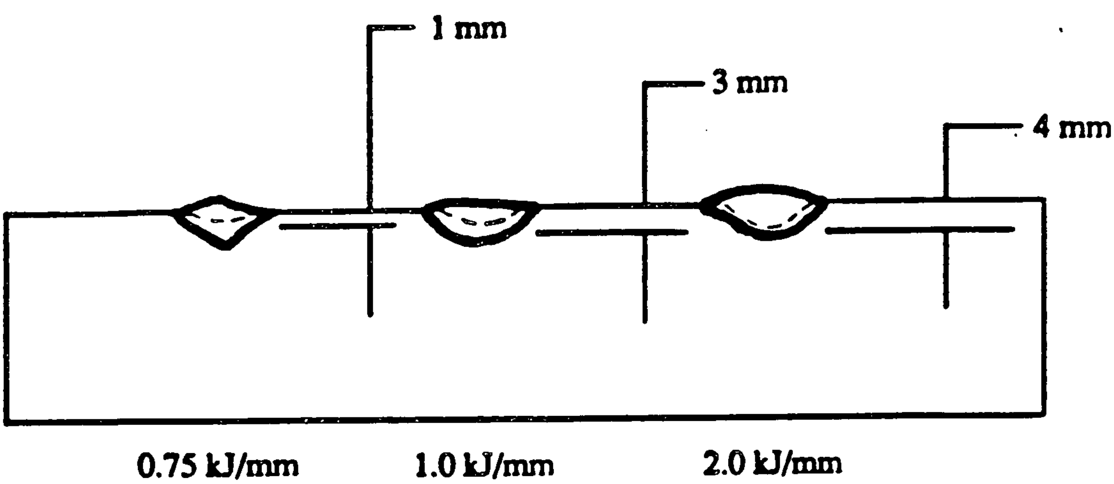
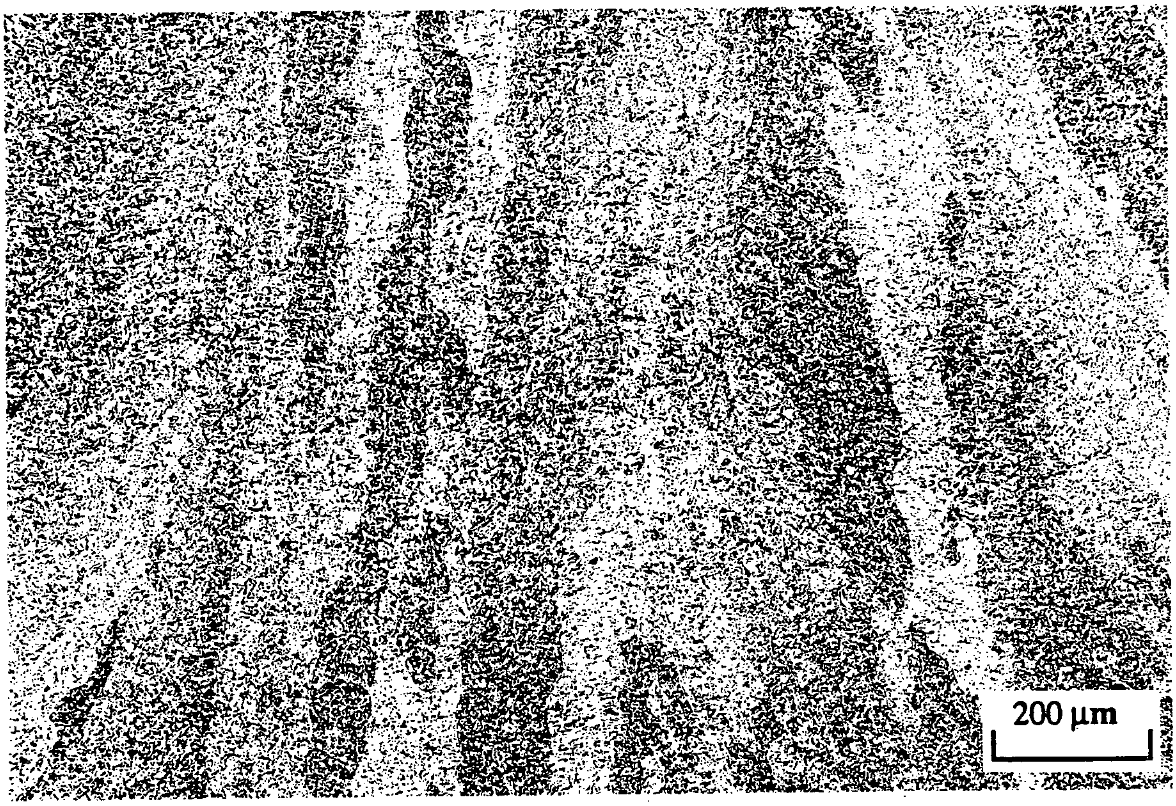
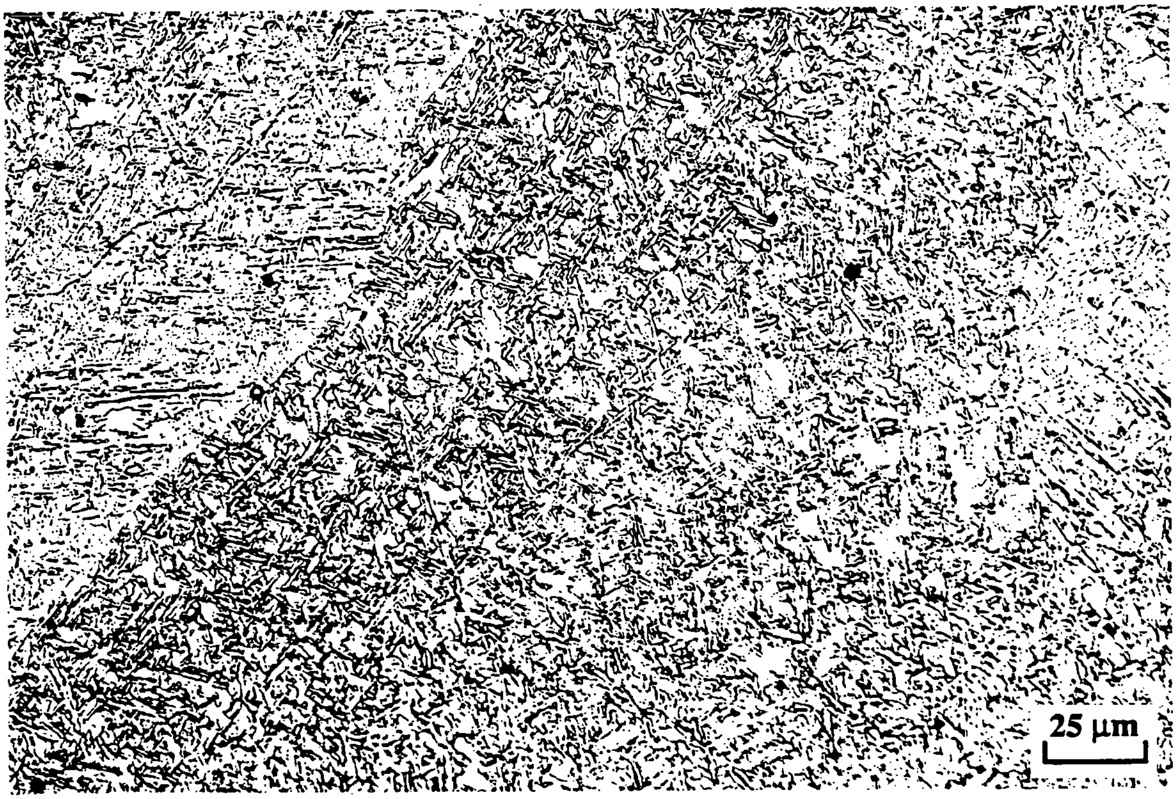


Fig. 2. Schematic diagram showing joint design preparation and bead shape for GMA bead-in groove welds.

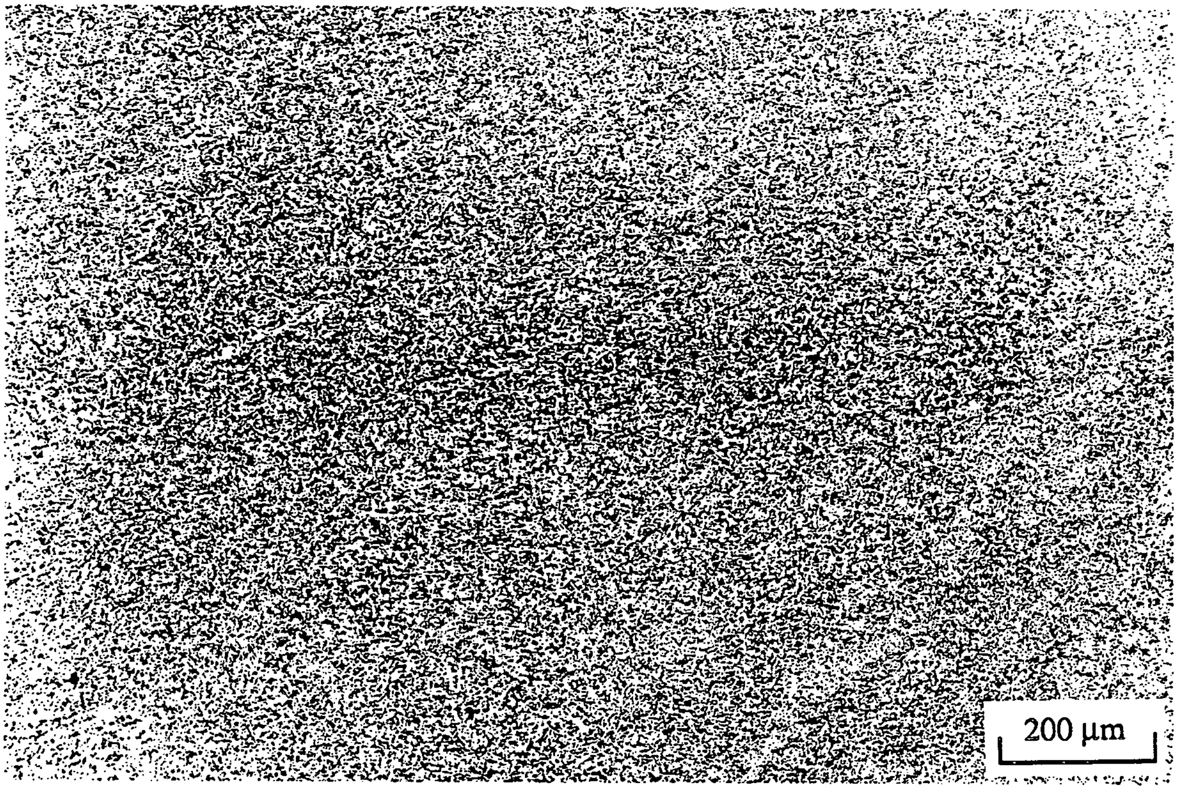


(a) columnar structure

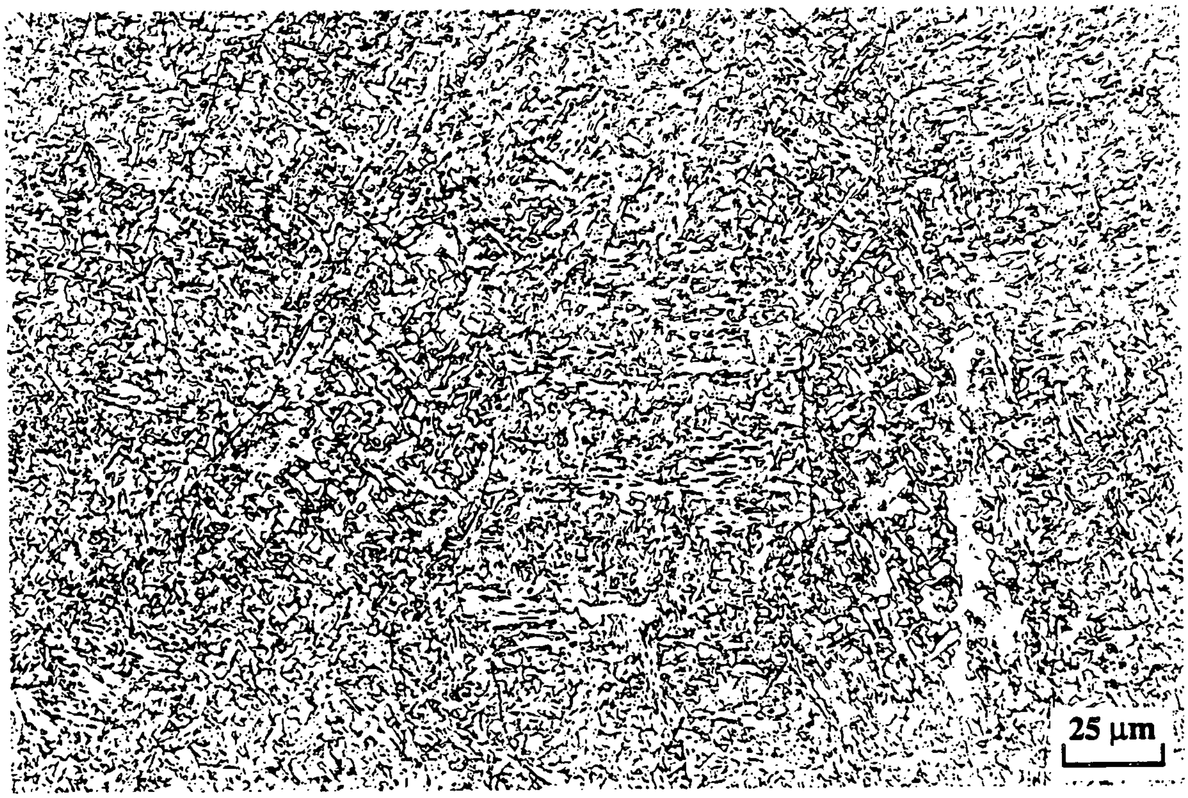


(b) microstructural constituents

Fig. 3. Optical micrographs showing microstructure of SA bead-in groove weld deposited at 1 kJ/mm in HSLA100 steel with the LTEC 120S1 and OP121TT consumables.

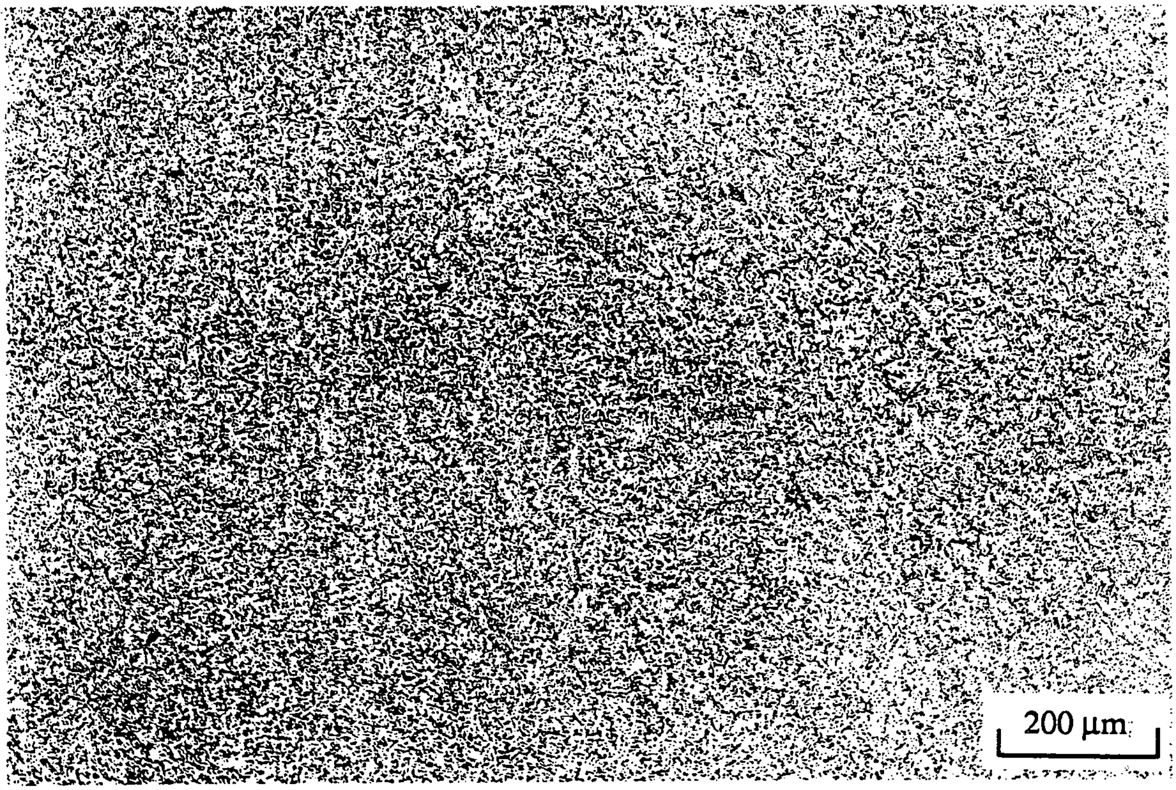


(a) columnar structure

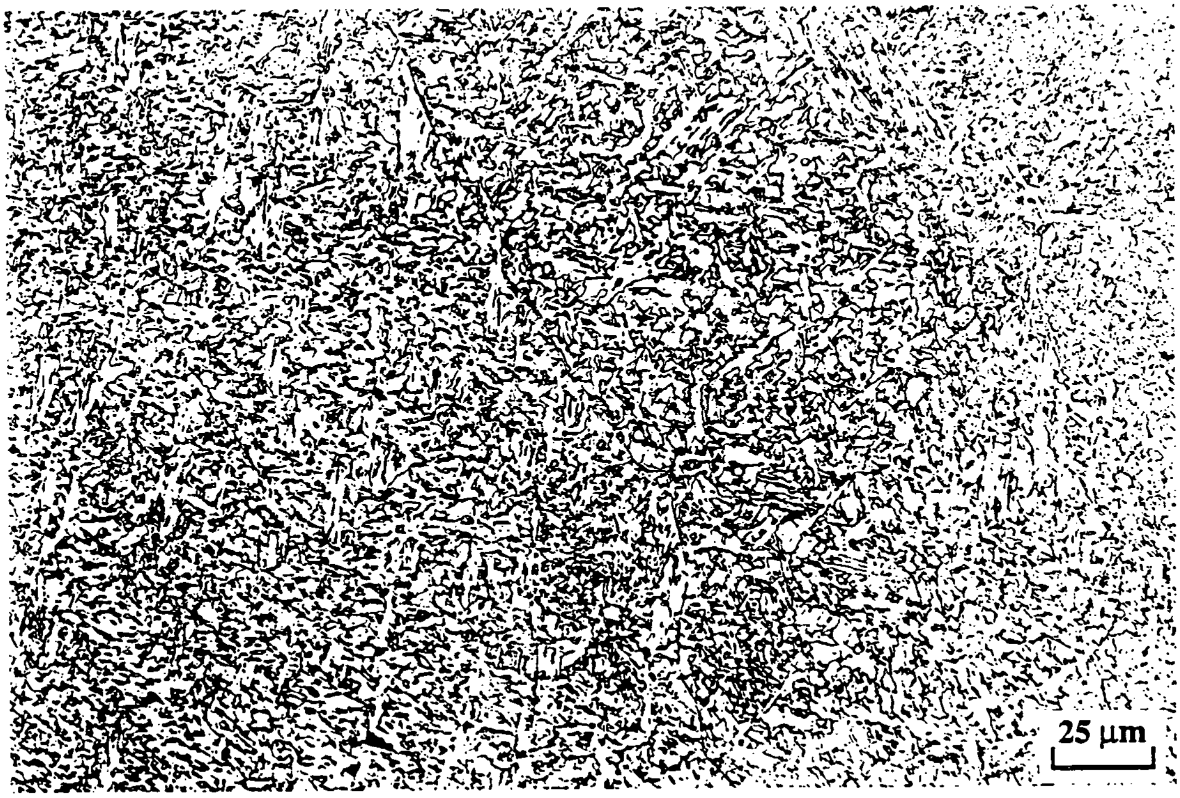


(b) microstructural constituents

Fig. 4. Optical micrographs showing microstructure of SA bead-in groove weld deposited at 2 kJ/mm in HSLA100 steel with the LTEC 120S1 and OP121TT consumables.

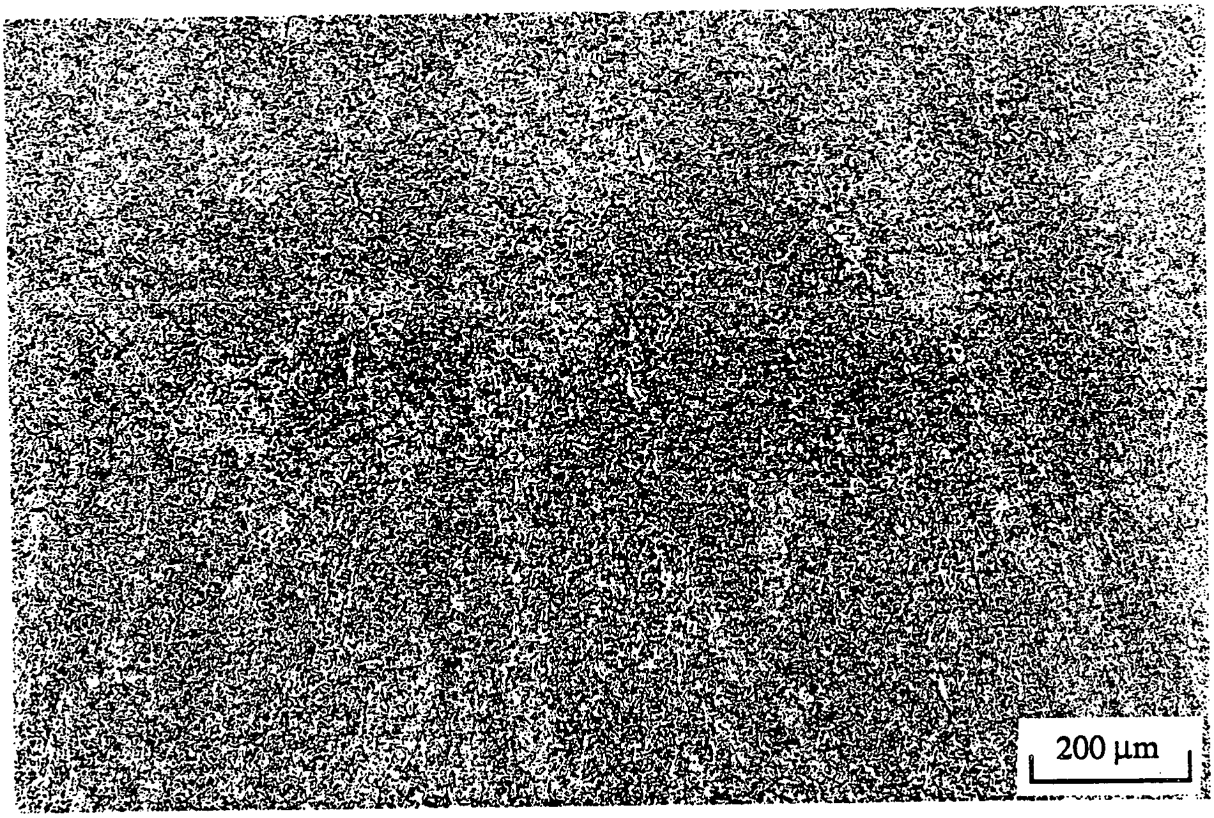


(a) columnar structure

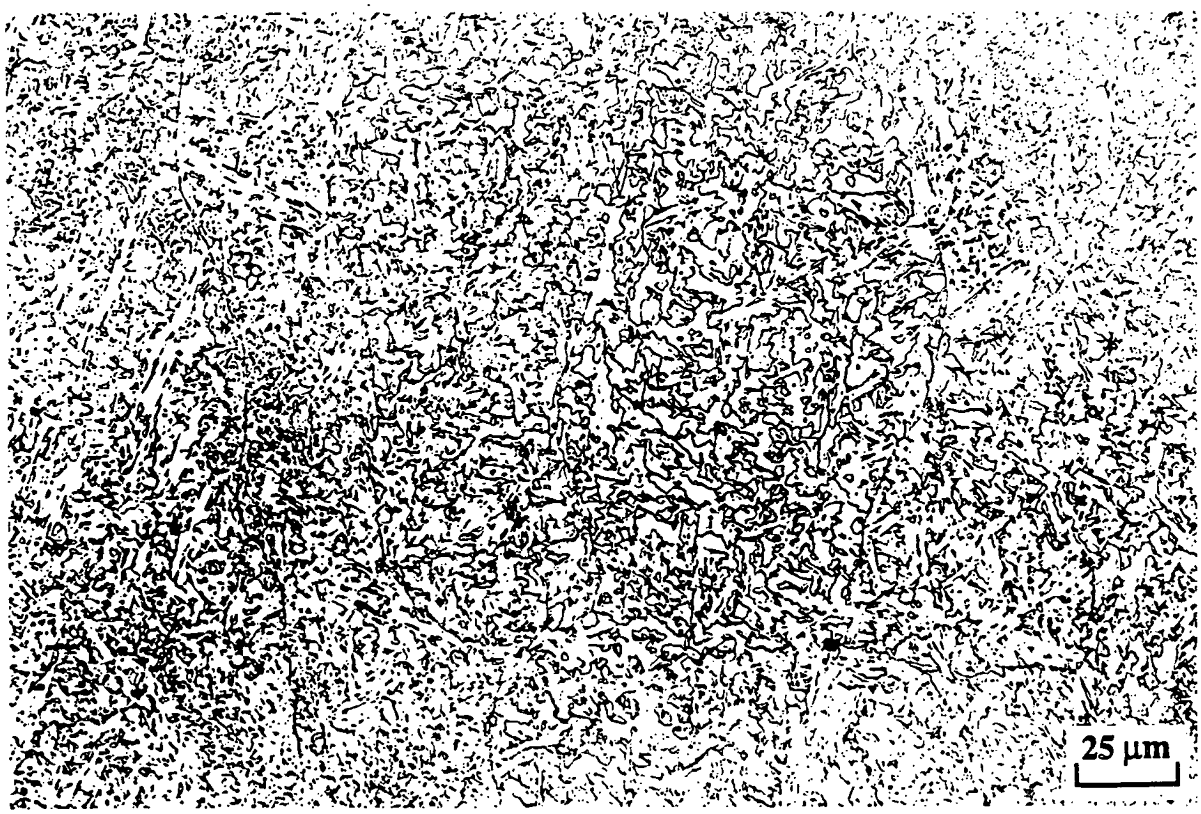


(b) microstructural constituents

Fig. 5. Optical micrographs showing microstructure of SA bead-in groove weld deposited at 3 kJ/mm in HSLA100 steel with the LTEC 120S1 and OP121TT consumables.

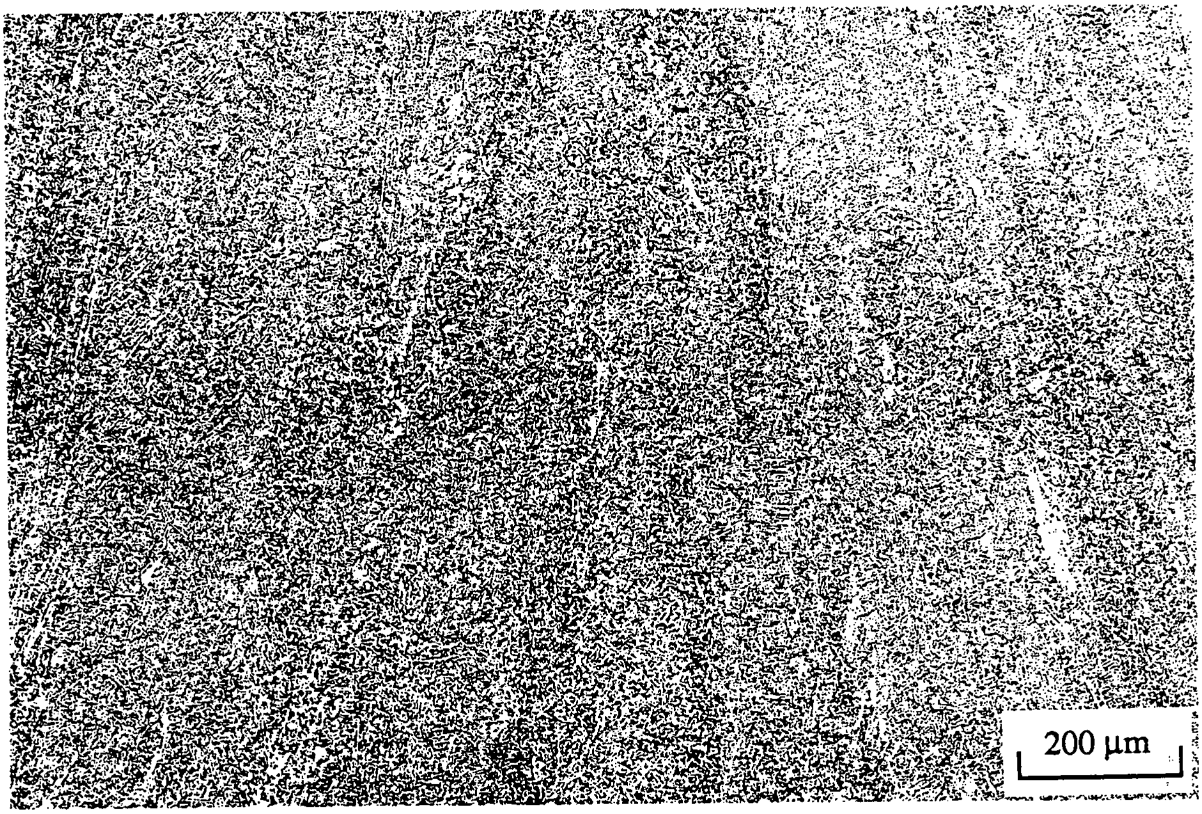


(a) columnar structure

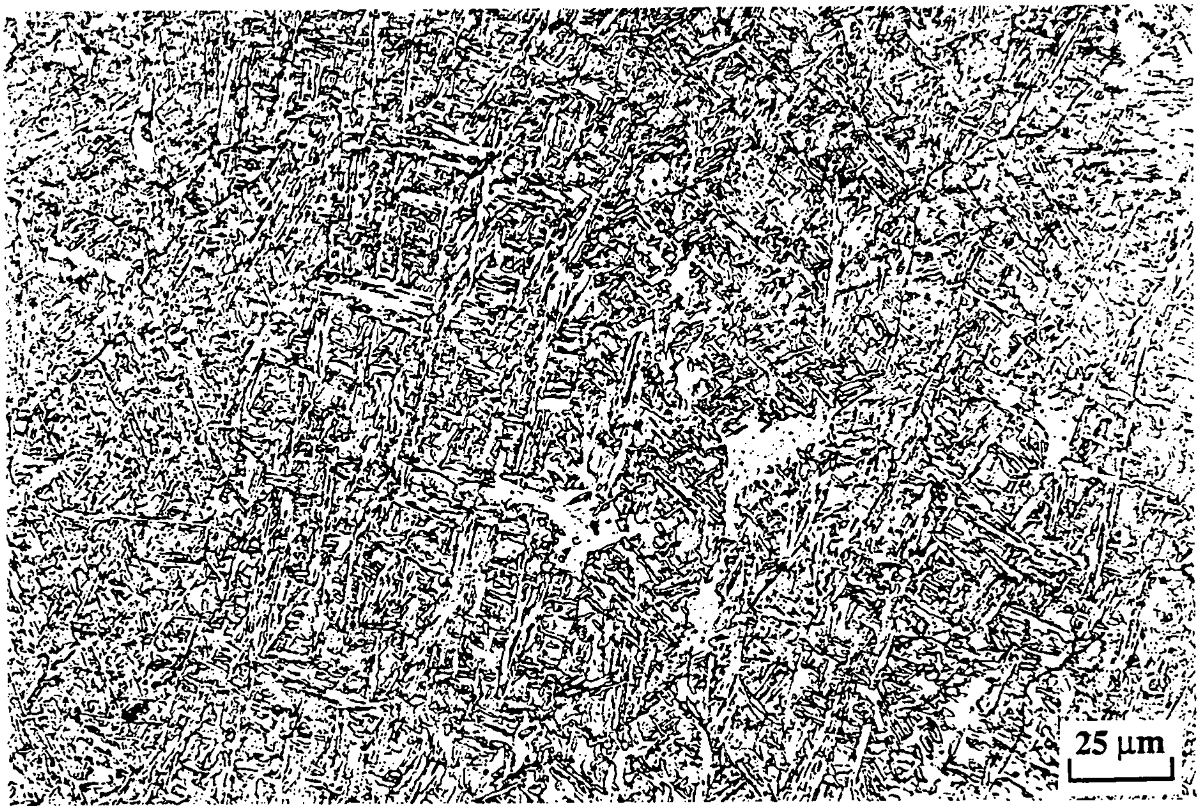


(b) microstructural constituents

Fig. 6. Optical micrographs showing microstructure of SA bead-in groove weld deposited at 4 kJ/mm in HSLA100 steel with the LTEC 120S1 and OP121TT consumables.

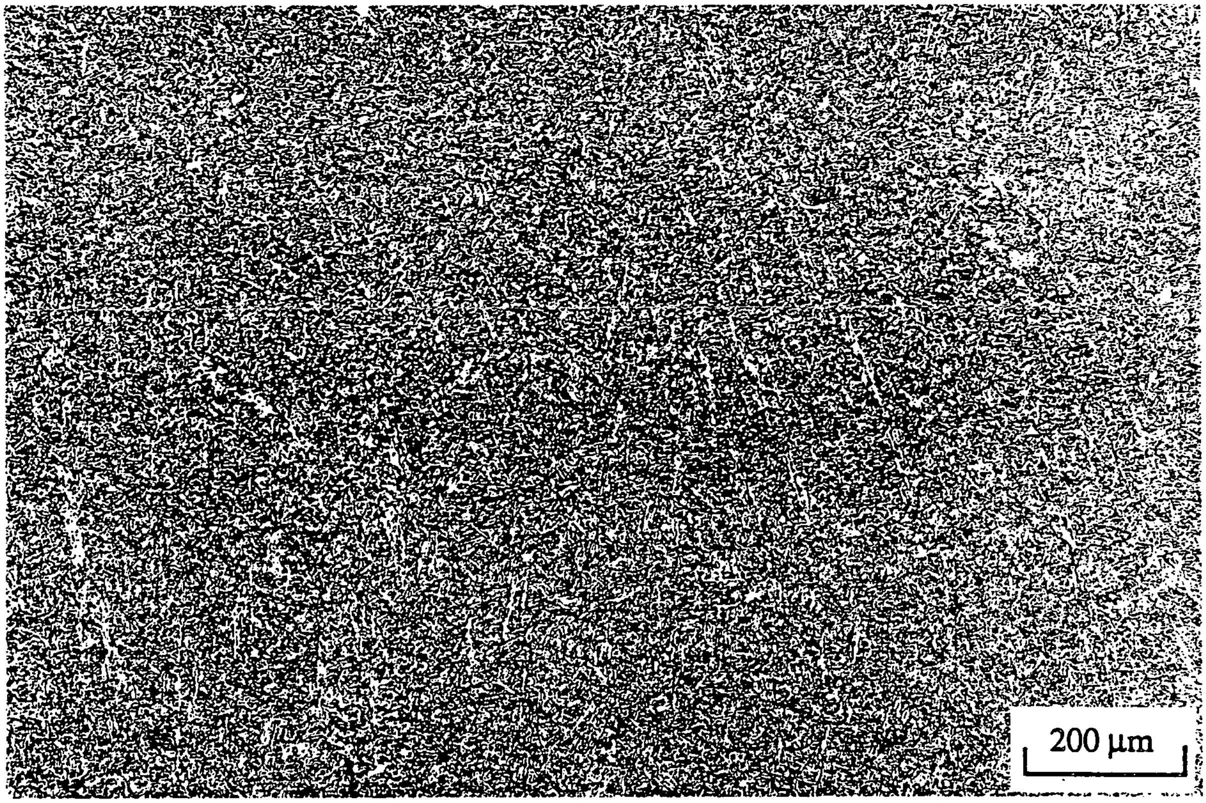


(a) columnar structure

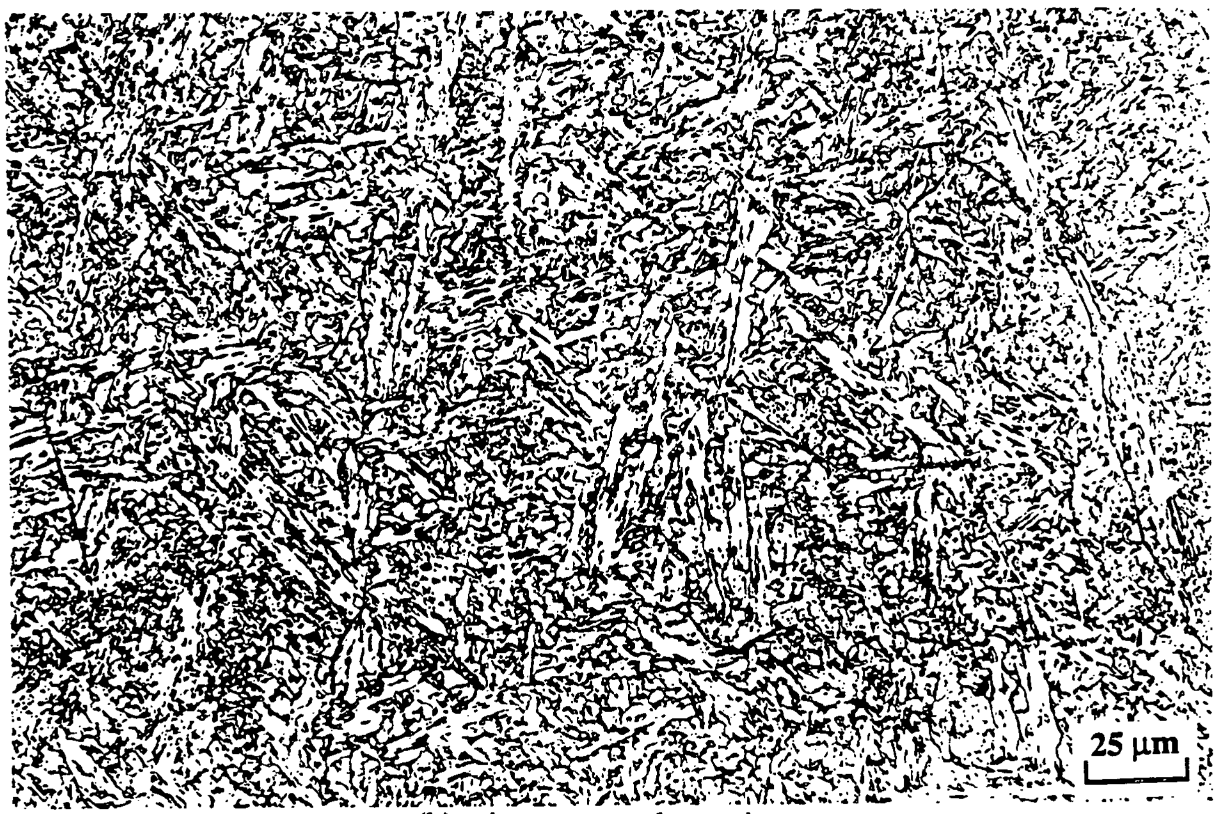


(b) microstructural constituents

Fig. 7. Optical micrographs showing microstructure of SA bead-in groove weld deposited at 1 kJ/mm in HSLA100 steel with the Kobe consumables.

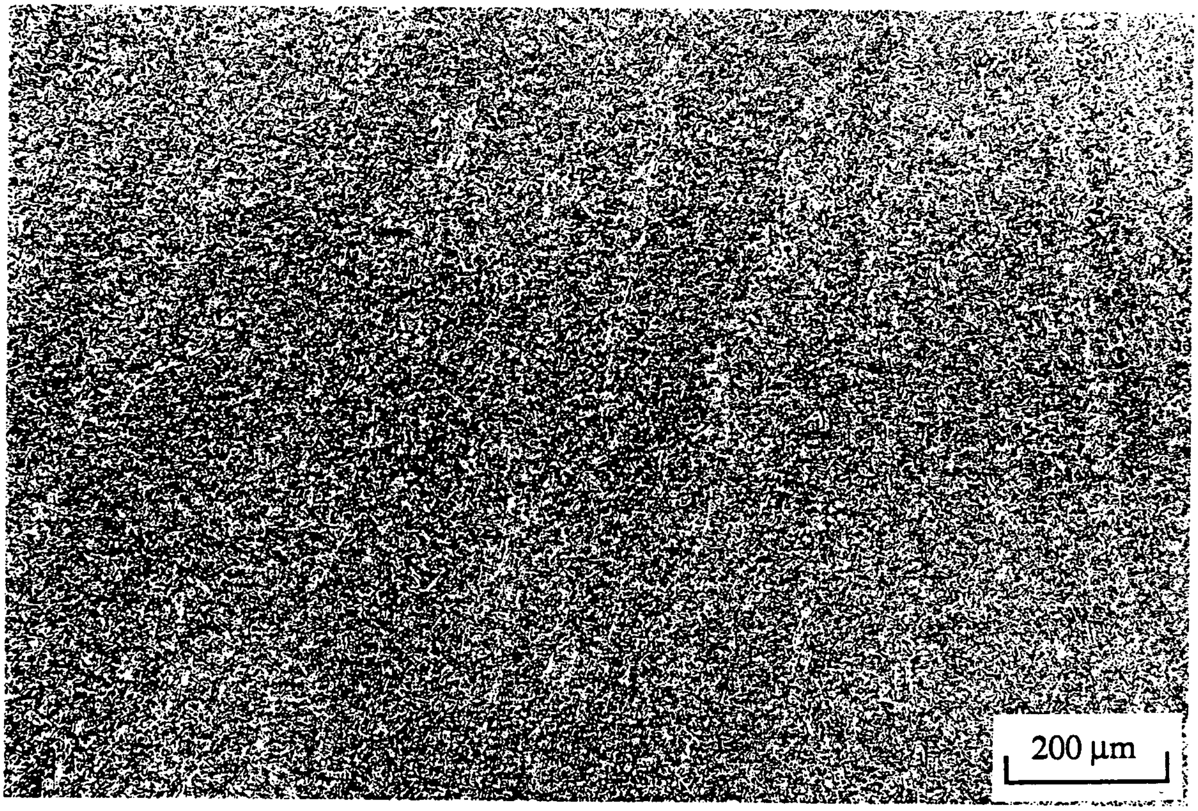


(a) columnar structure

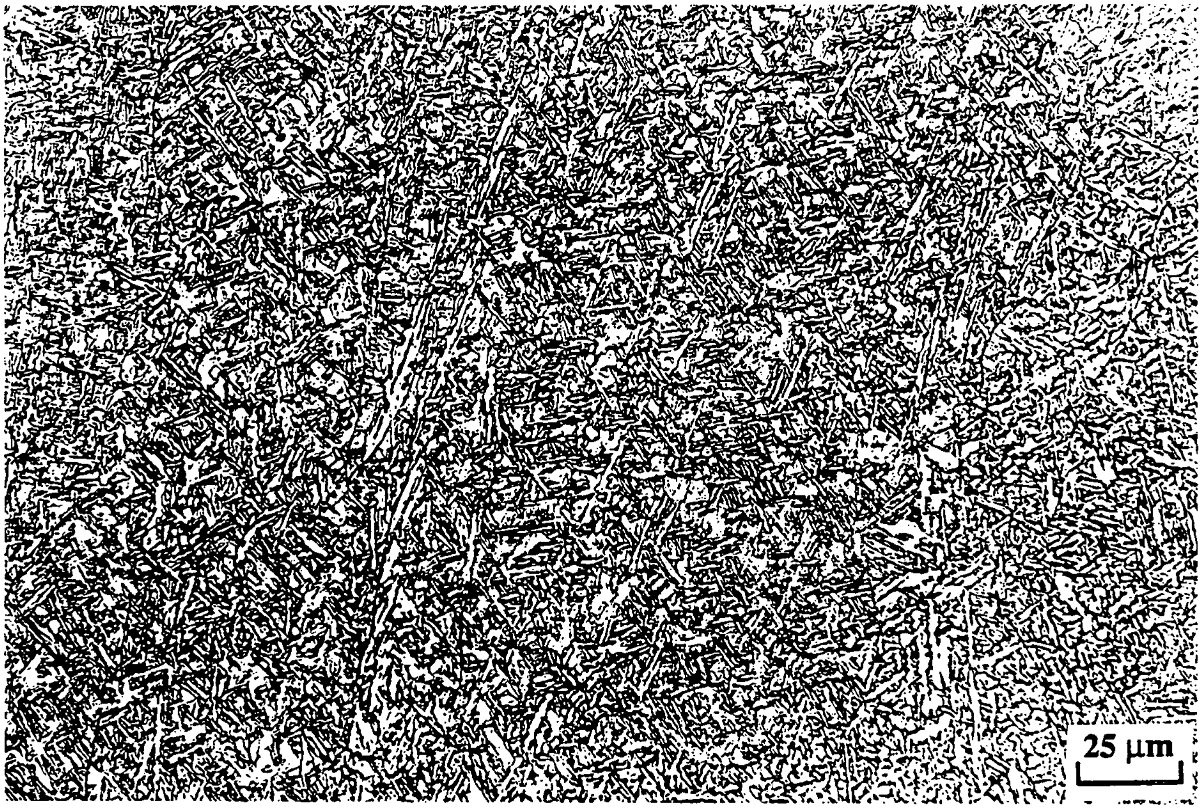


(b) microstructural constituents

Fig. 8. Optical micrographs showing microstructure of SA bead-in groove weld deposited at 4 kJ/mm in HSLA100 steel with the Kobe consumables.

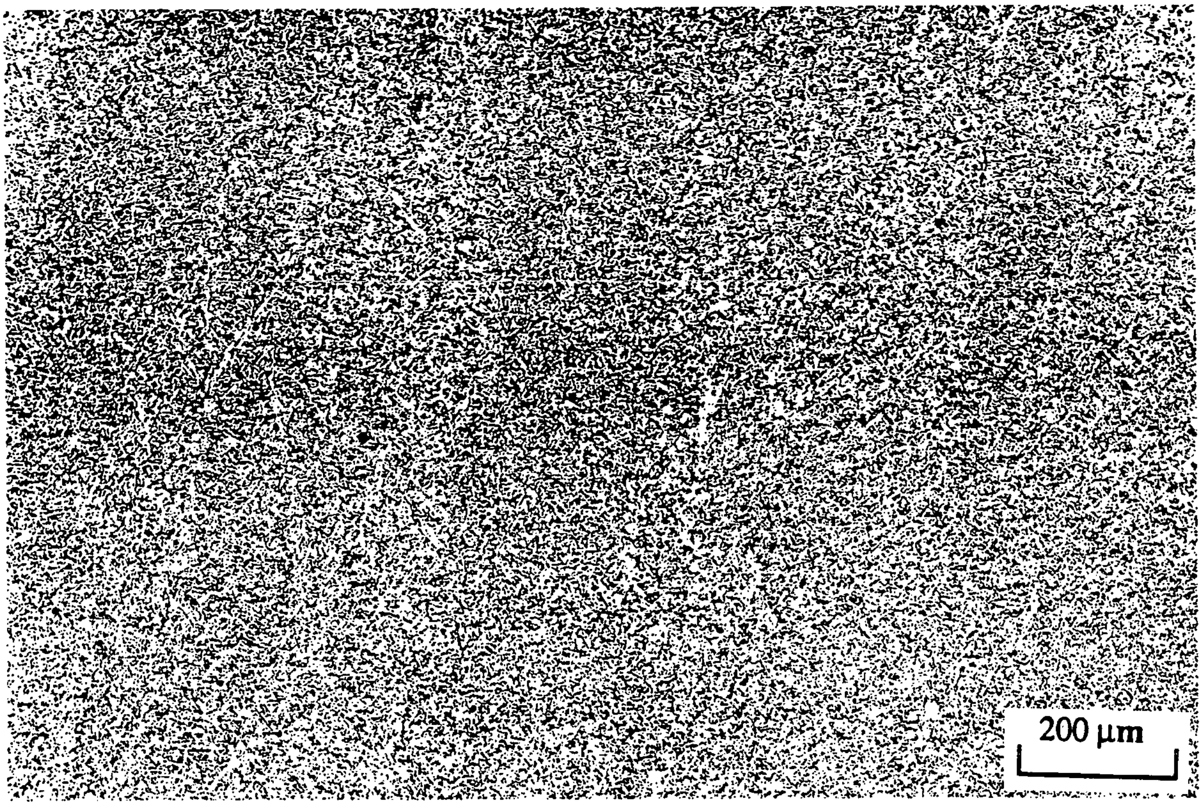


(a) columnar structure

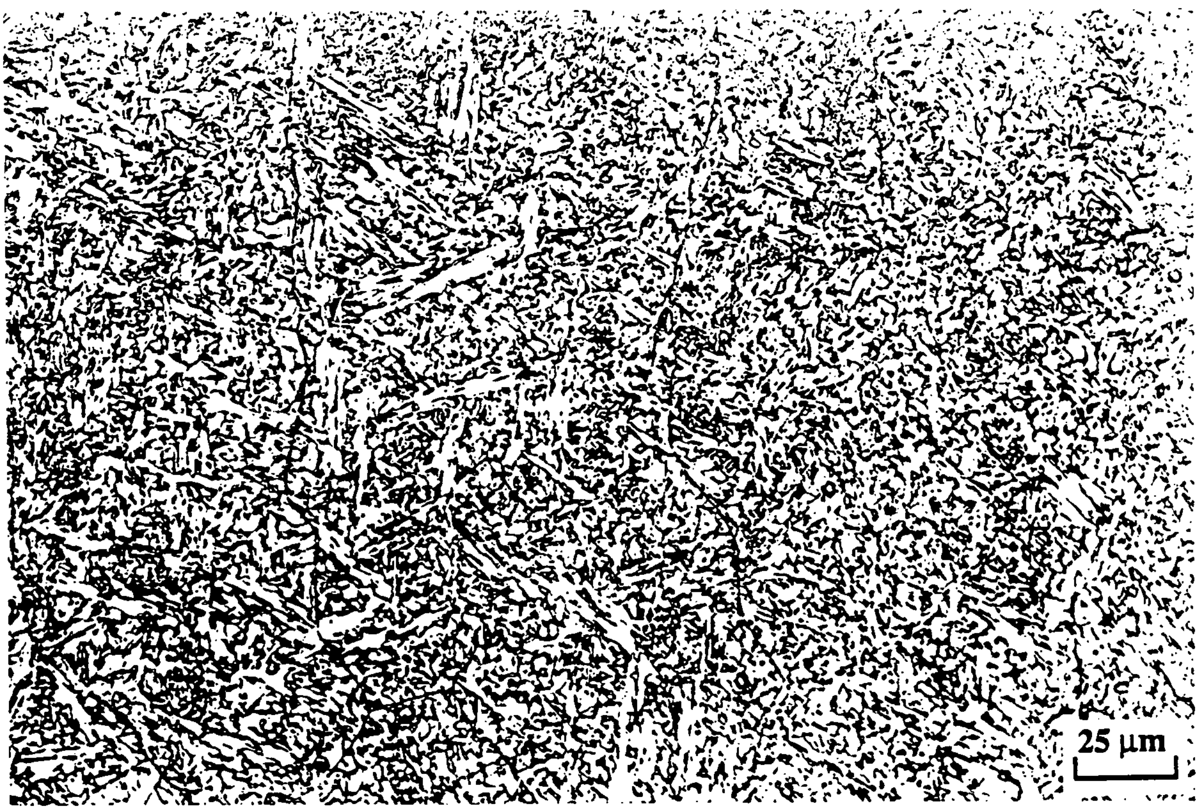


(b) microstructural constituents

Fig. 9. Optical micrographs showing microstructure of SA bead-in groove weld deposited at 1 kJ/mm in HSLA100 steel with the Thyssen consumables.



(a) columnar structure



(b) microstructural constituents

Fig. 10. Optical micrographs showing microstructure of SA bead-in groove weld deposited at 4 kJ/mm in HSLA100 steel with the Thyssen consumables.

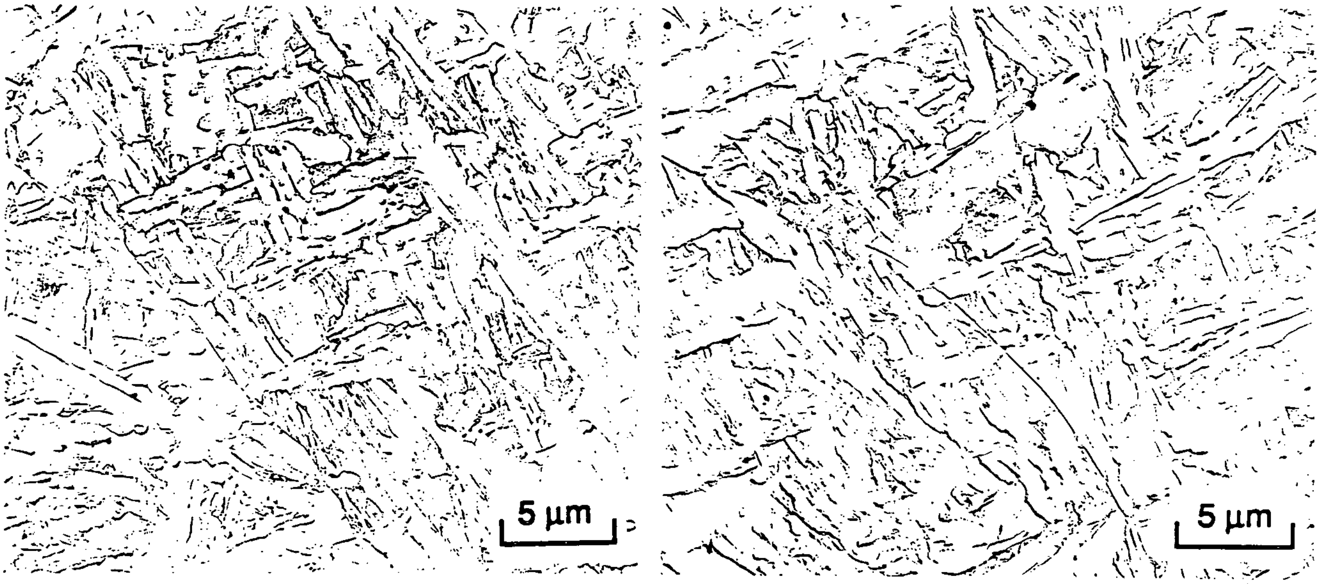


Fig. 11. TEM micrograph from extraction replica of series A bead-in groove weld deposited at 1 kJ/mm.

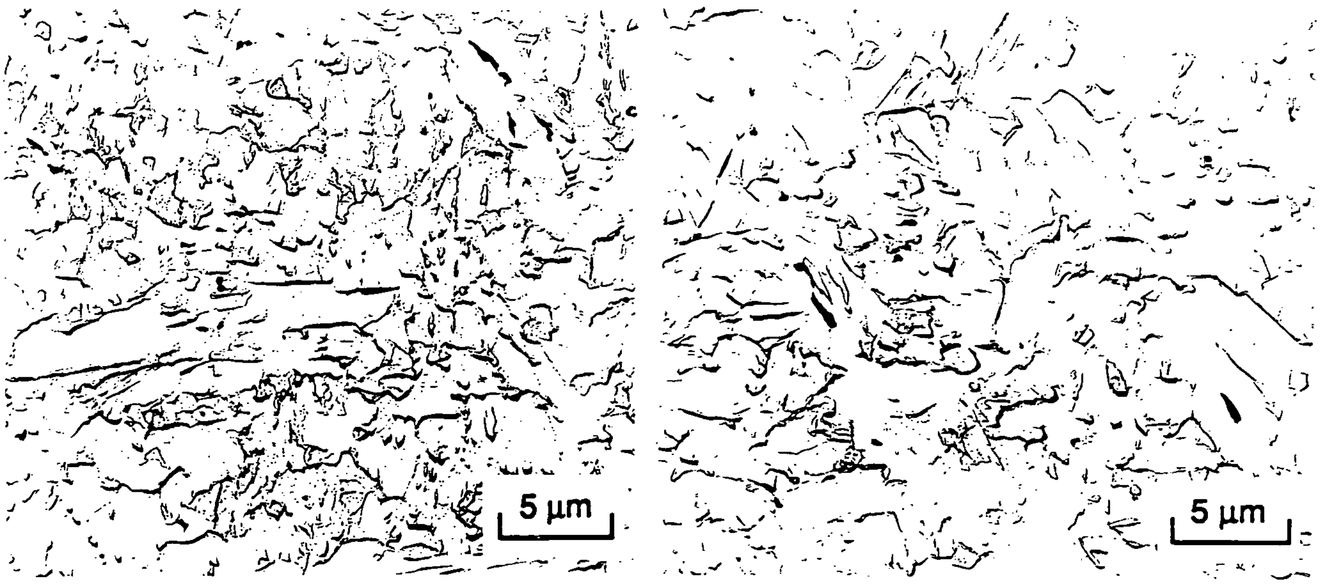
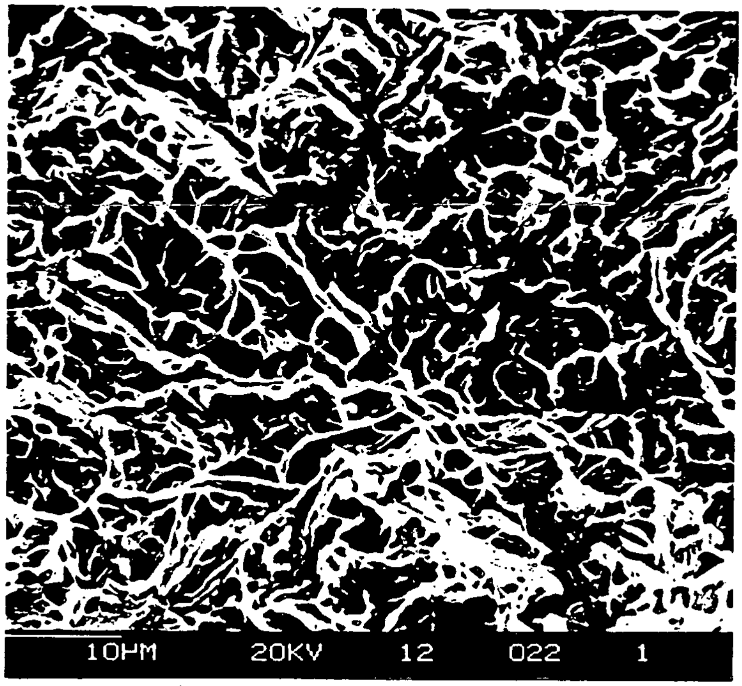
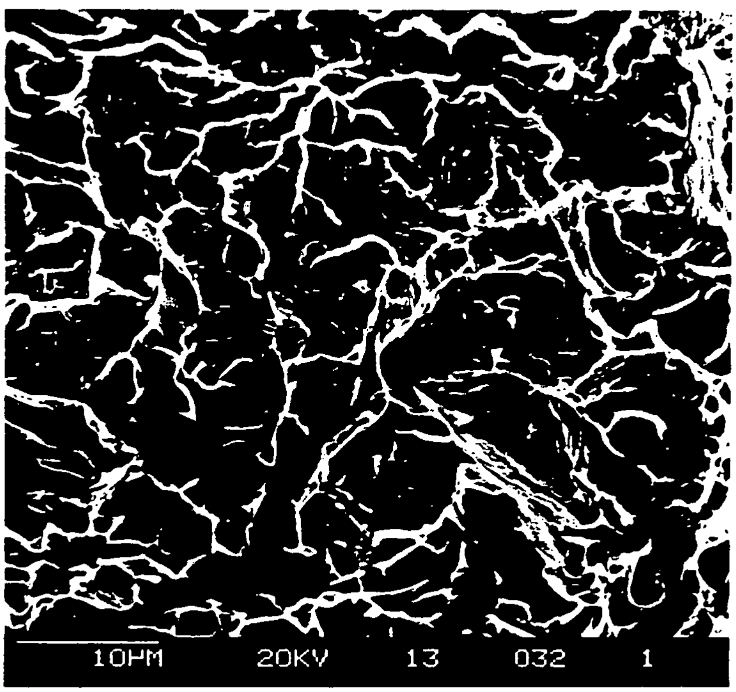


Fig. 12. TEM micrograph from extraction replica of series A bead-in groove weld deposited at 4 kJ/mm.

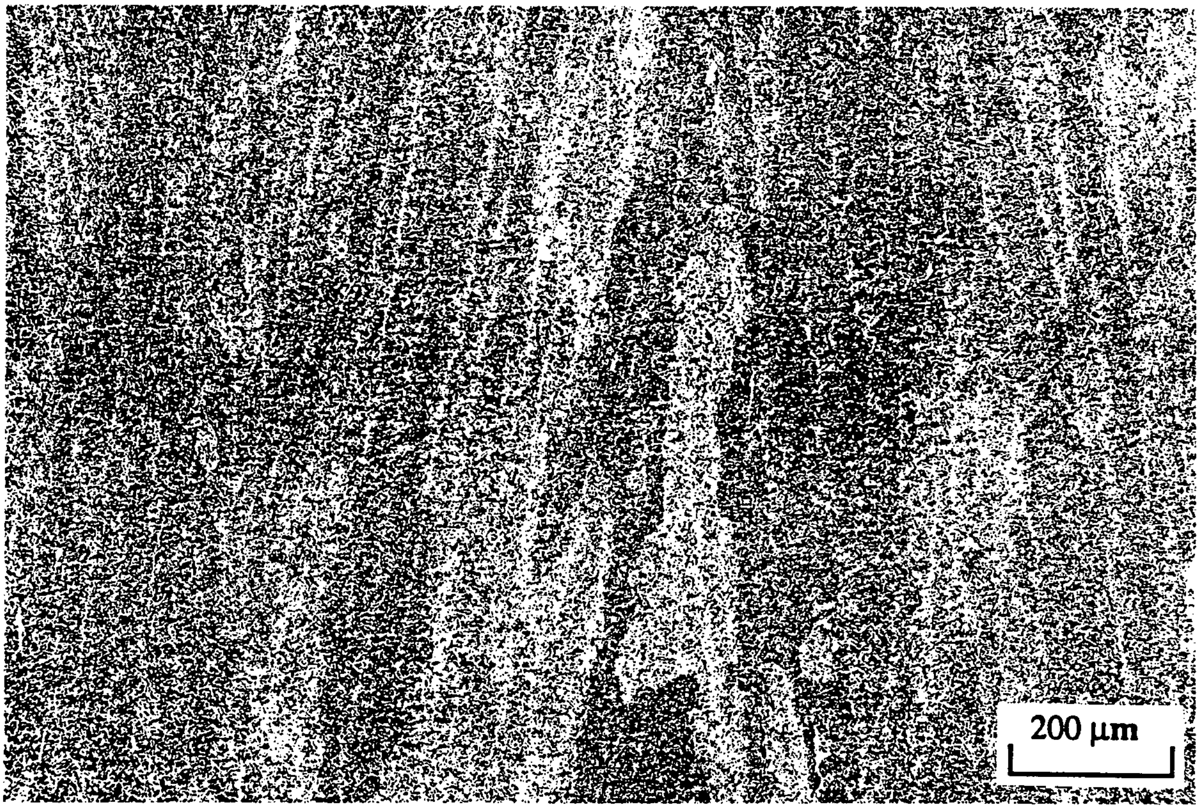


(a) 1 kJ/mm energy input

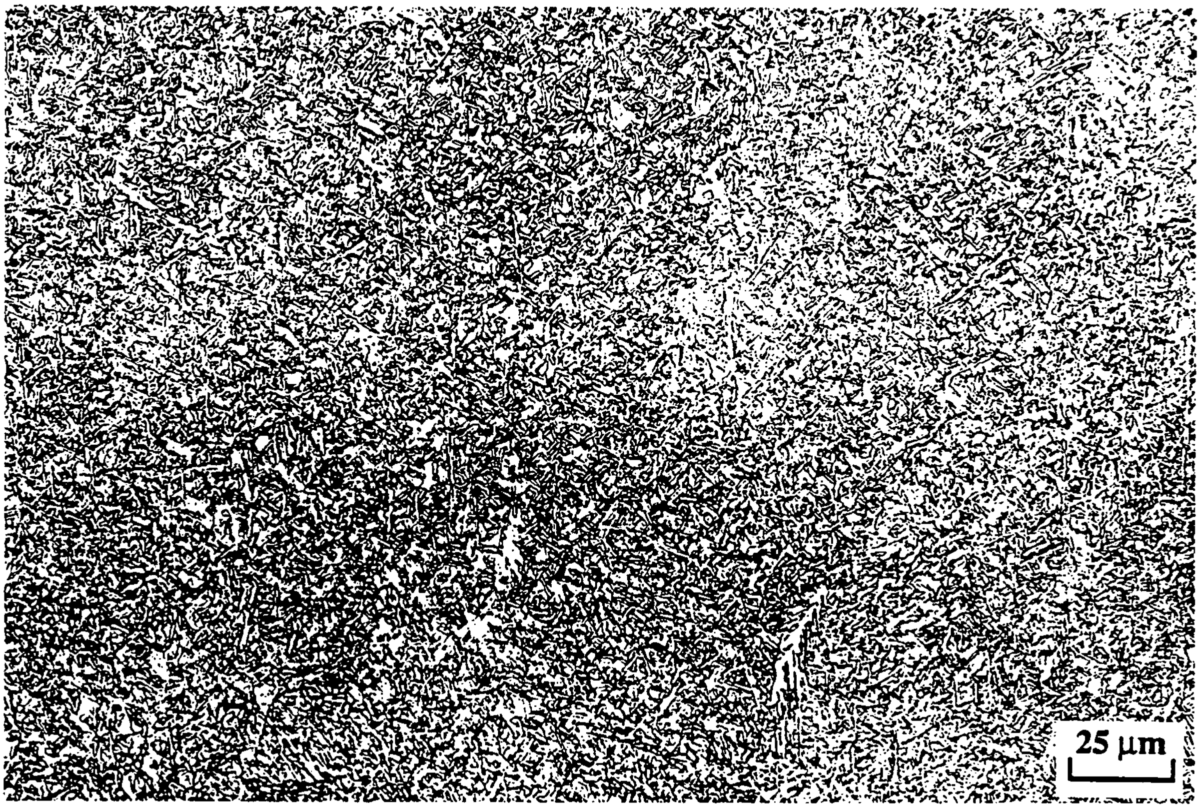


(b) 4 kJ/mm energy input

Fig. 13. SEM fractograph of Charpy specimen from SA bead-in groove weld tested at -196°C. LTEC 120S1 and OP121TT consumable combination.

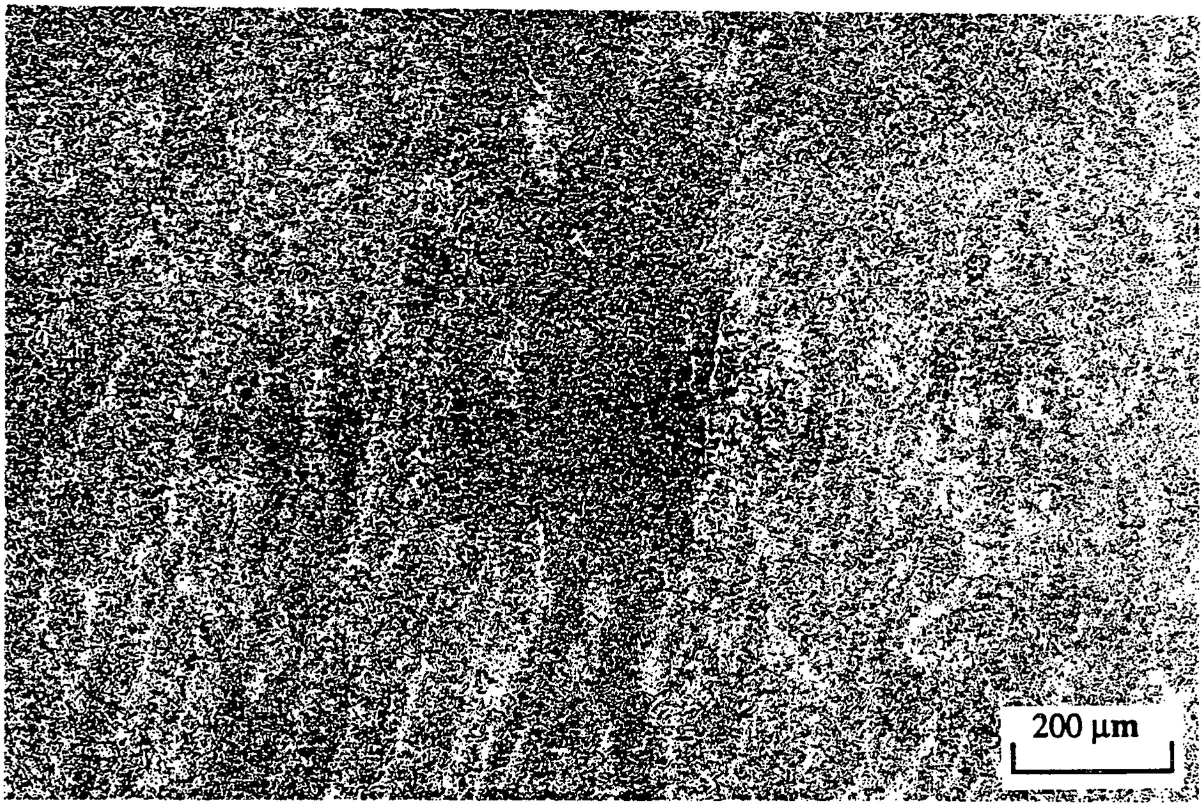


(a) columnar structure

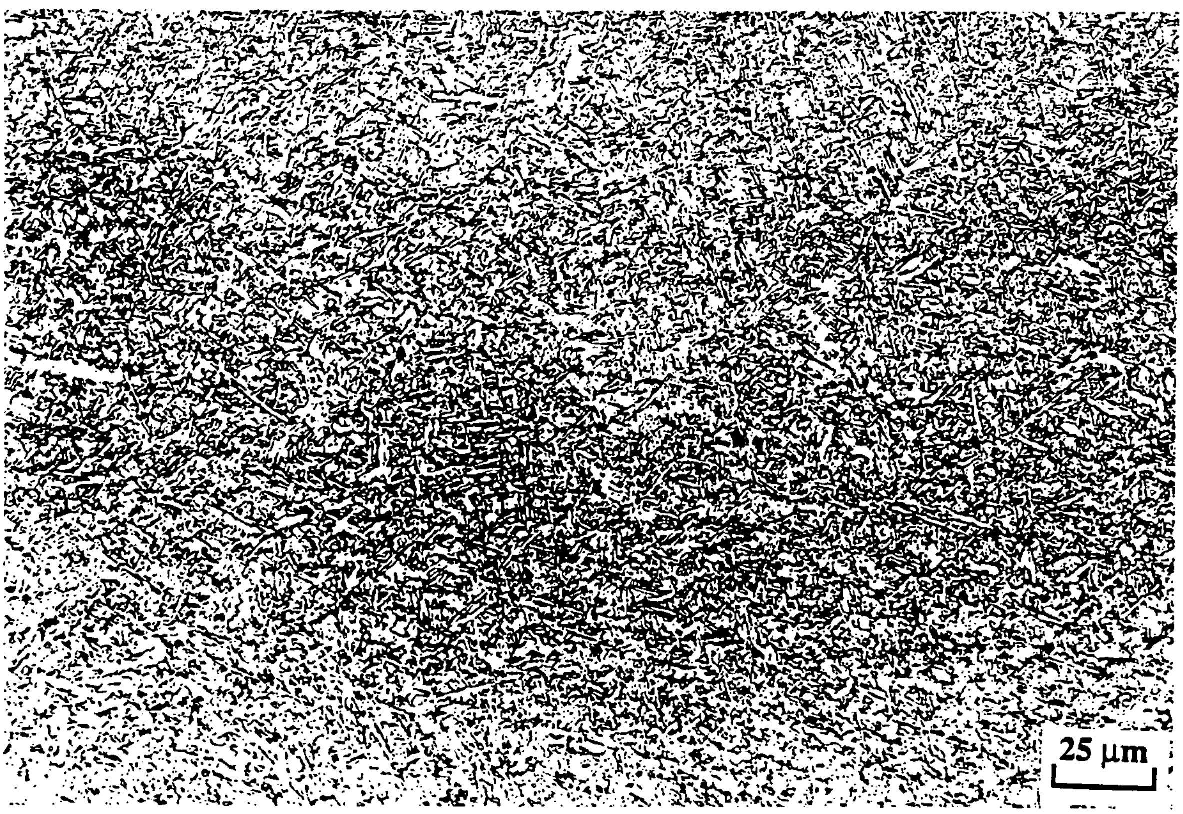


(b) microstructural constituents

Fig. 14. Optical micrographs showing microstructure of GMA bead-in groove weld deposited at ~0.75 kJ/mm in HSLA100 steel with the LTEC 120S1 and C20 shielding gas.

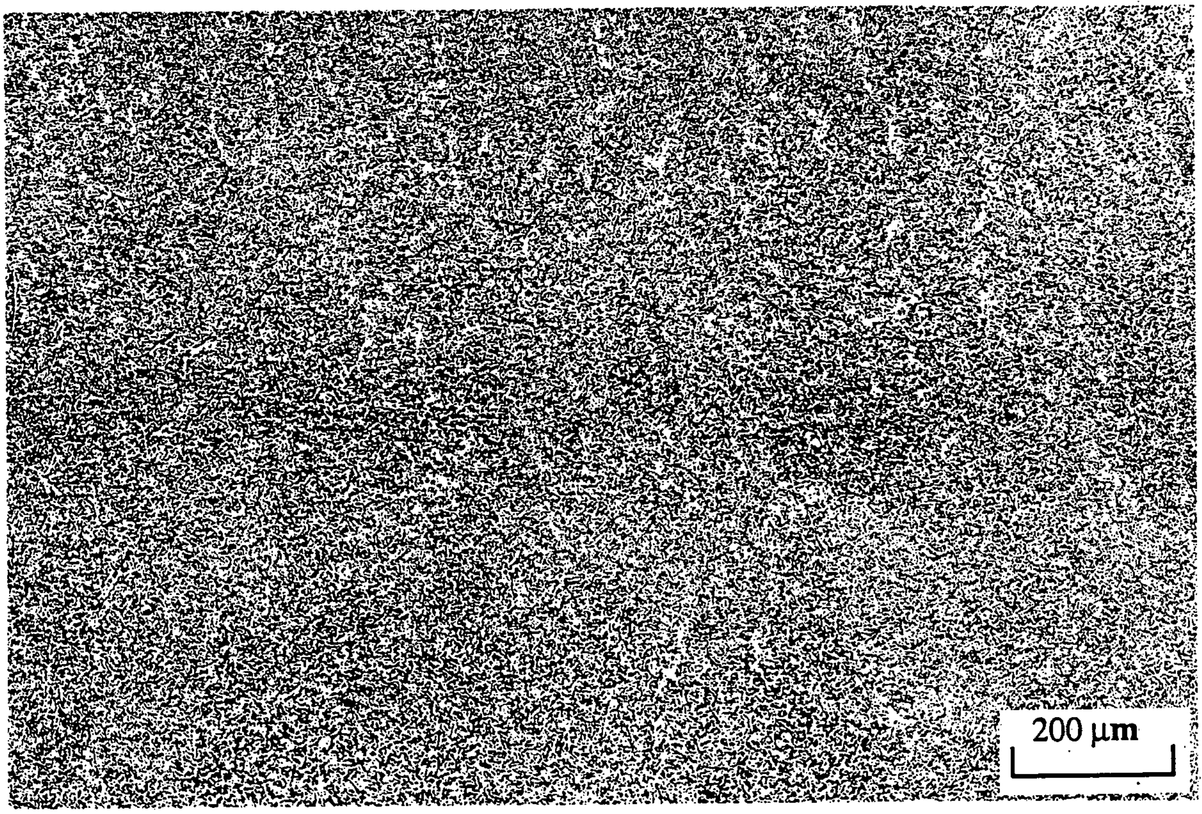


(a) columnar structure

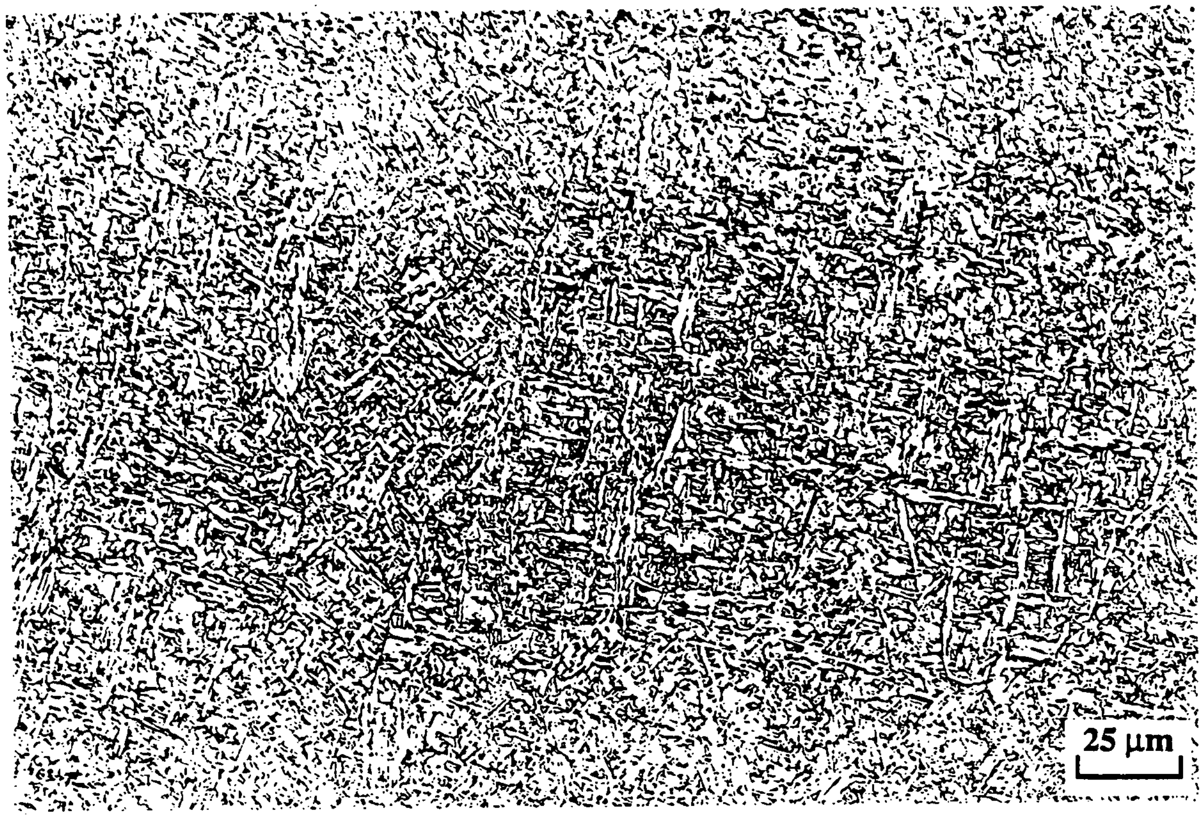


(b) microstructural constituents

Fig. 15. Optical micrographs showing microstructure of GMA bead-in groove weld deposited at ~1.0 kJ/mm in HSLA100 steel with the LTEC 120S1 and C20 shielding gas.

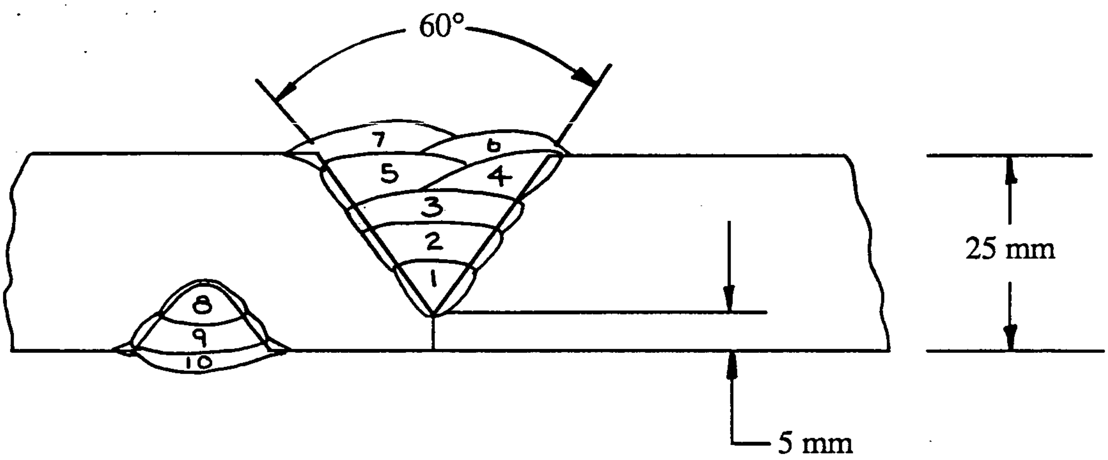


(a) columnar structure

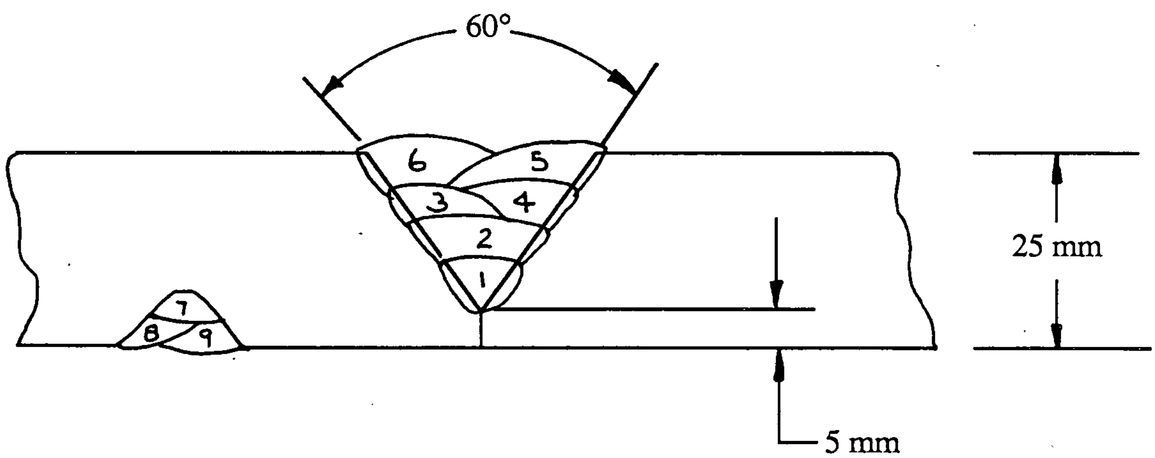


(b) microstructural constituents

Fig. 16. Optical micrographs showing microstructure of GMA bead-in groove weld deposited at ~2.0 kJ/mm in HSLA100 steel with the LTEC 120S1 and C20 shielding gas.

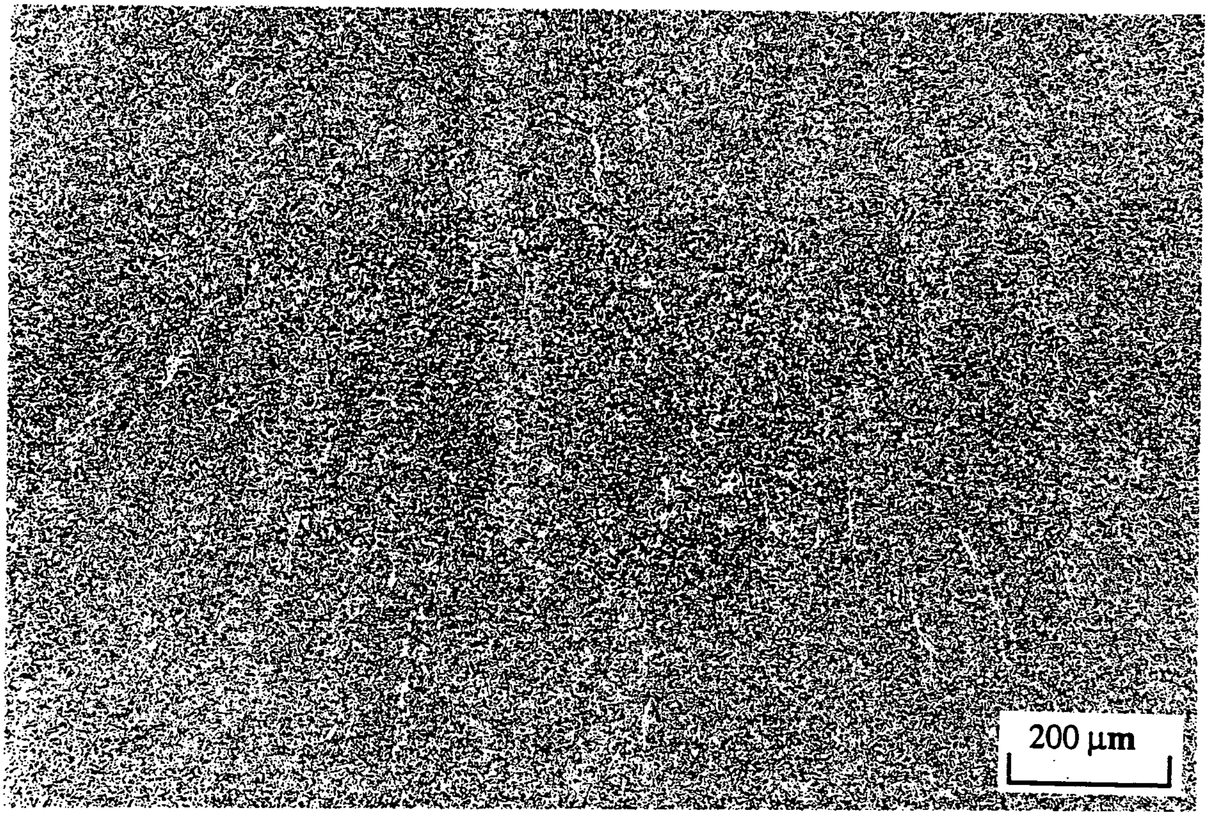


(a) SA weld

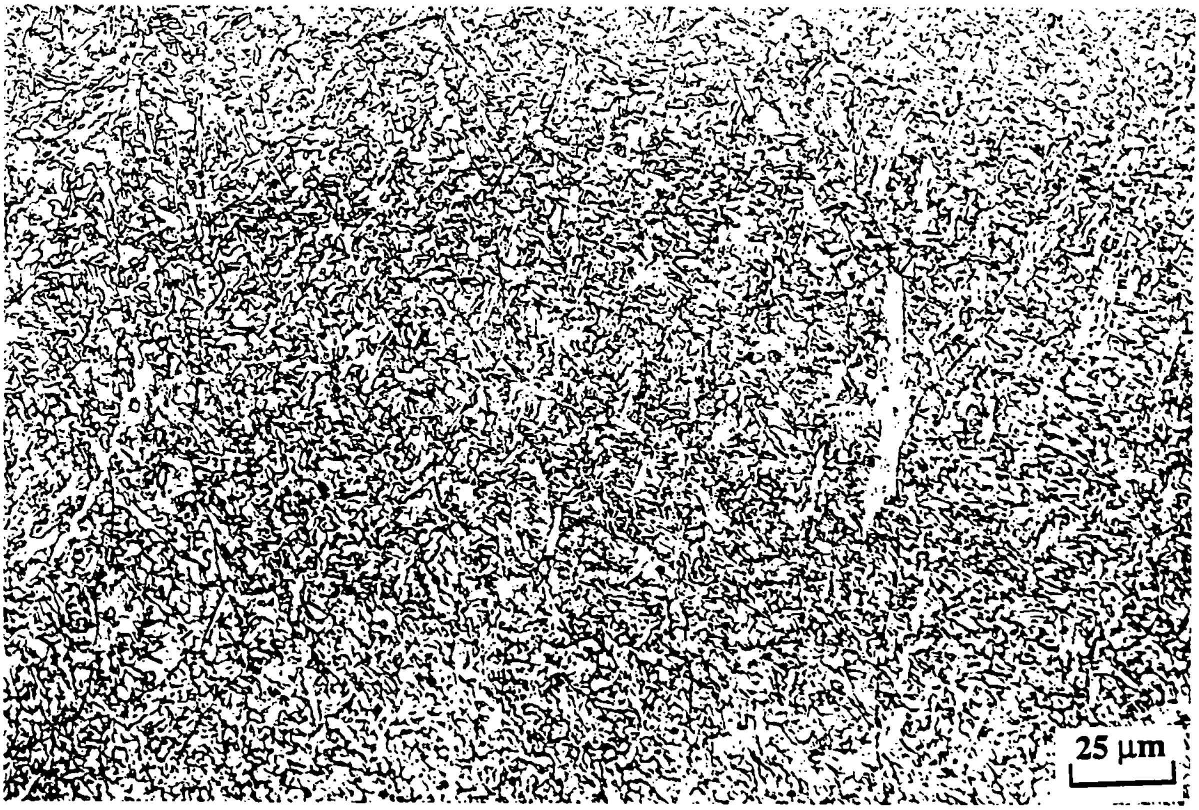


(b) GMA weld

Fig. 17. Weld joint design preparation and pass sequence for full thickness welds prepared in HSLA100 steel.

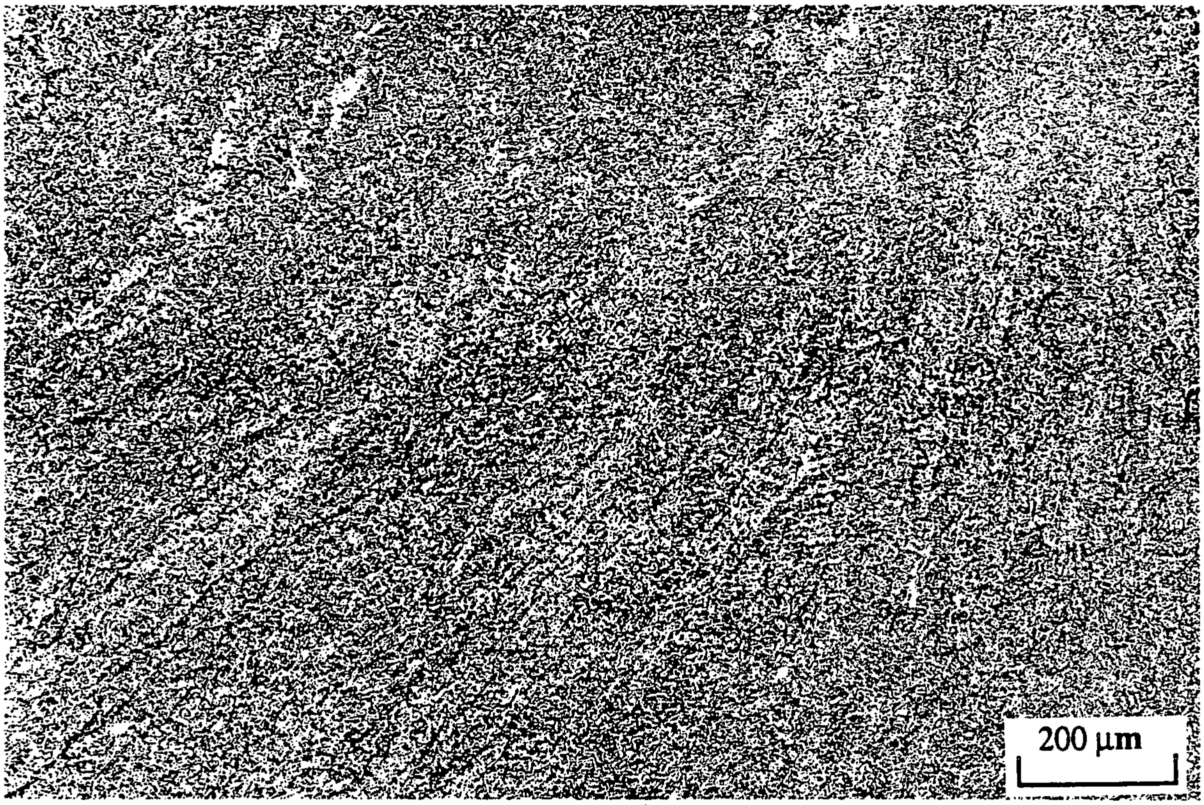


(a) columnar structure

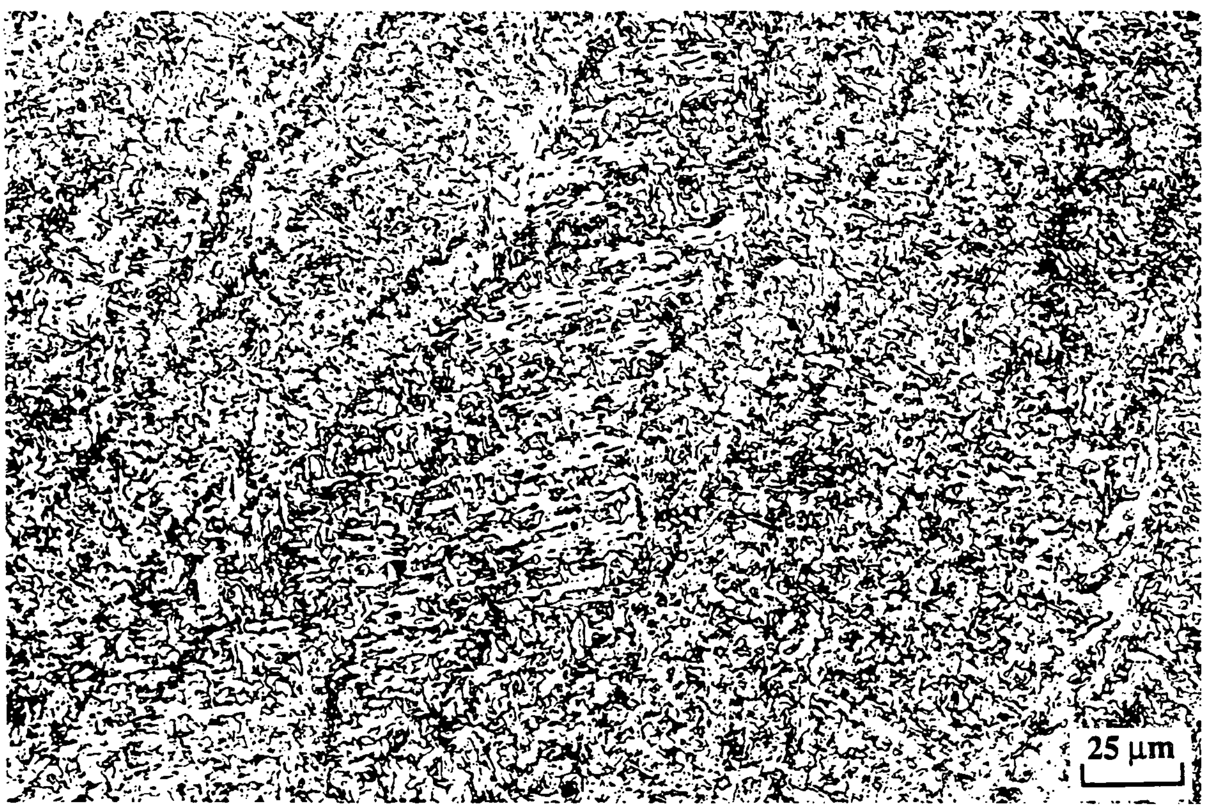


(b) microstructural constituents

Fig. 18. Optical micrographs showing as-deposited microstructure of SA full thickness weld deposited at 2 kJ/mm in HSLA100 steel with the LTEC 120S1 and OP121TT consumables.

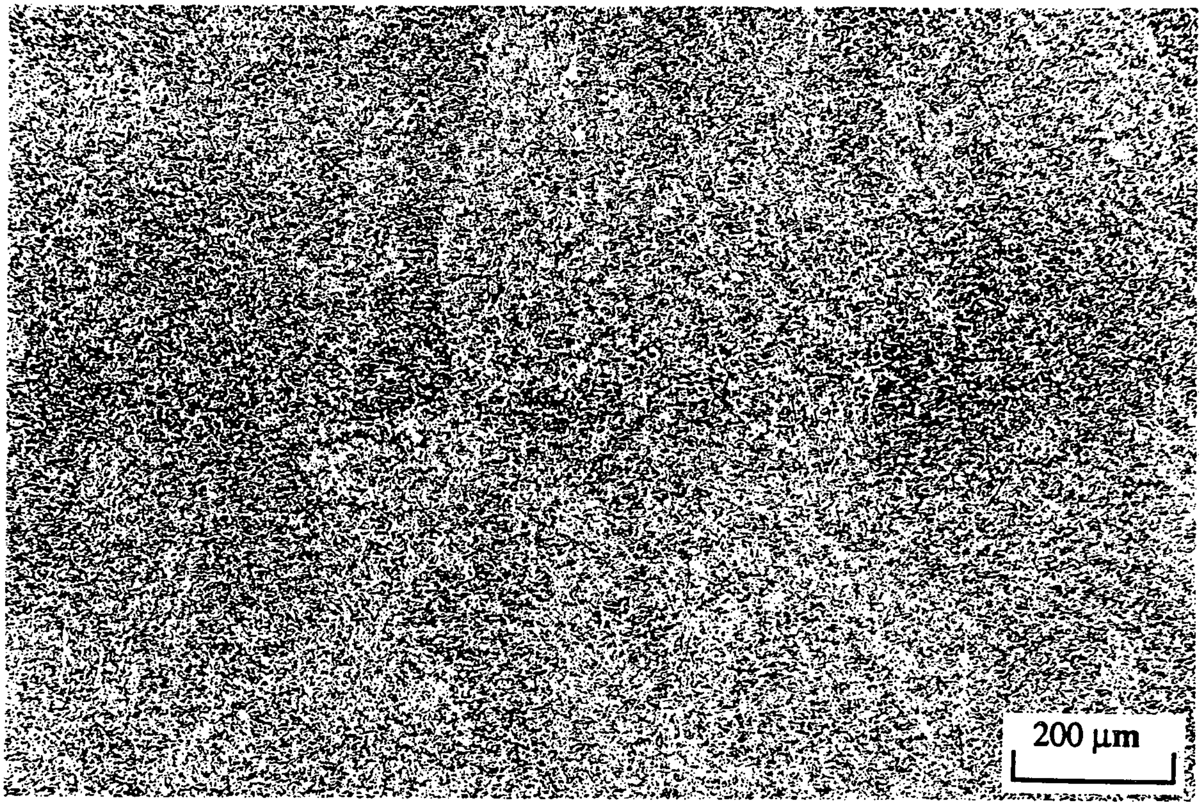


(a) reheated structure

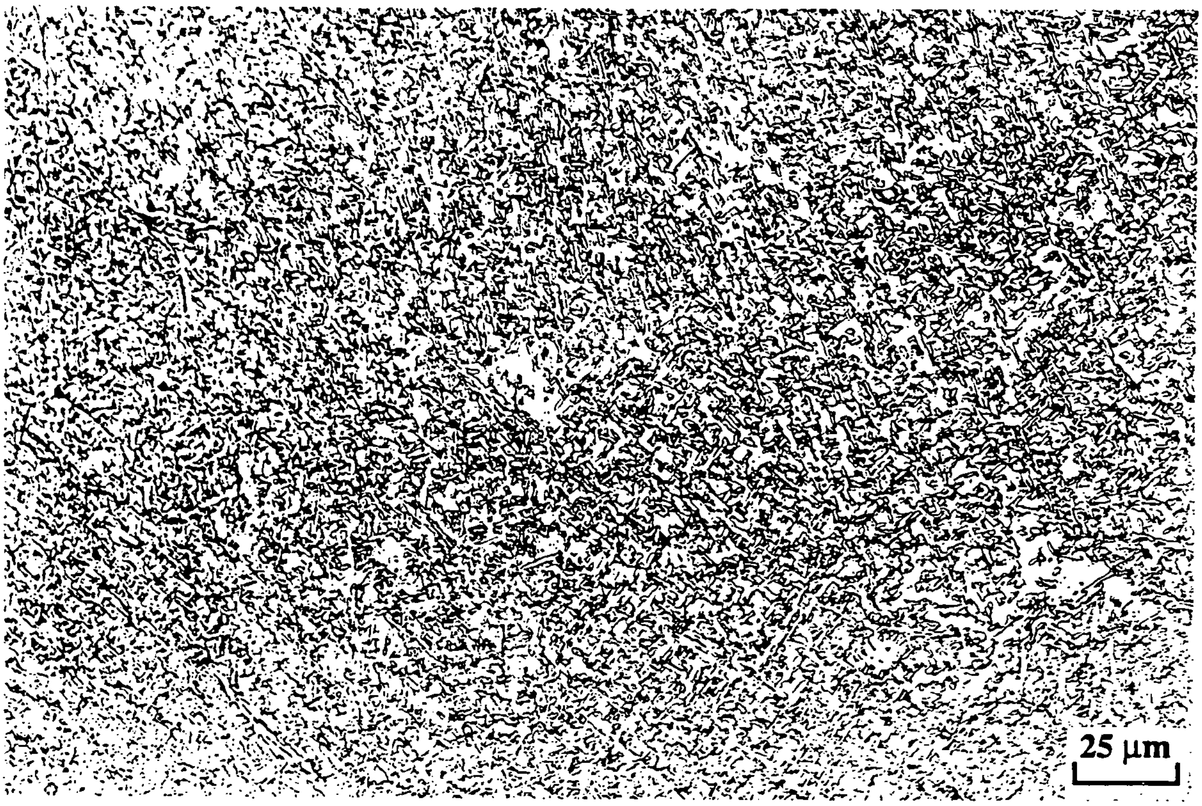


(b) microstructural constituents

Fig. 19. Optical micrographs showing reheated microstructure of SA full thickness weld deposited at 2 kJ/mm in HSLA100 steel with the LTEC 120S1 and OP121TT consumables.

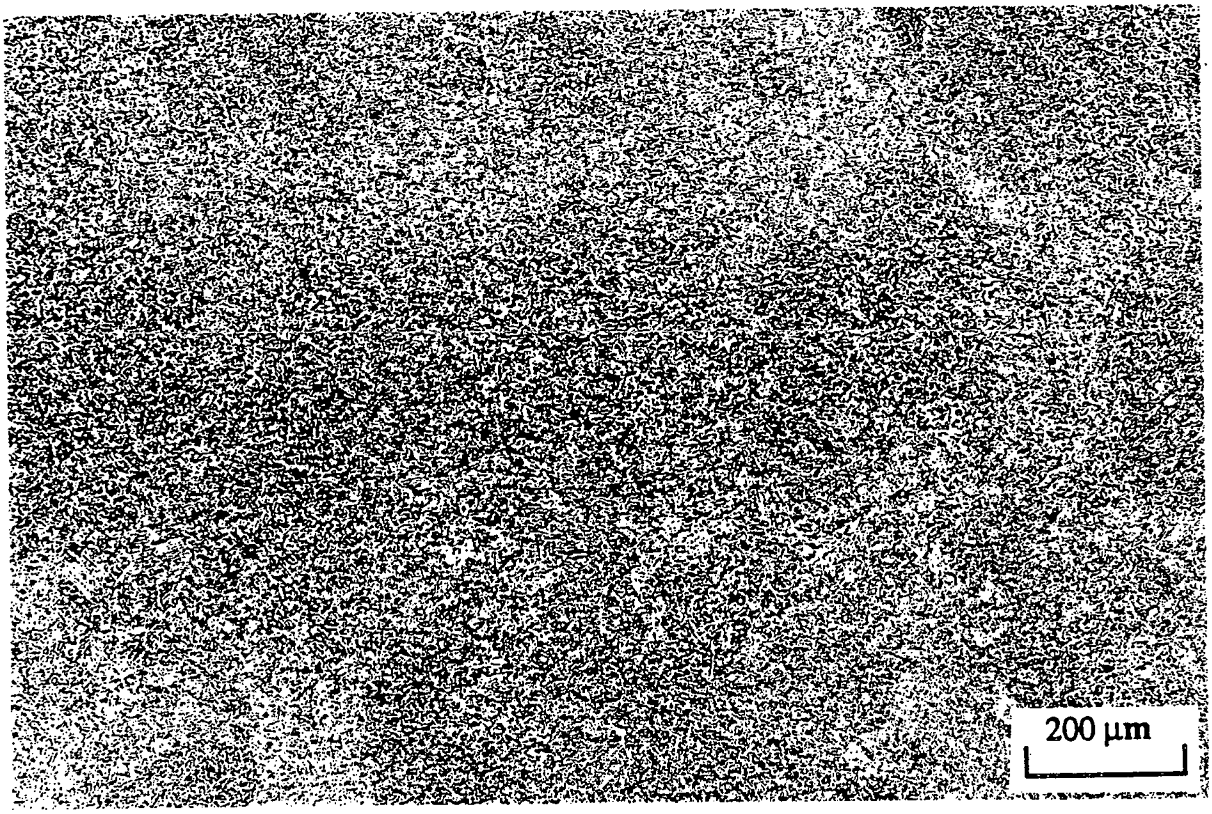


(a) columnar structure

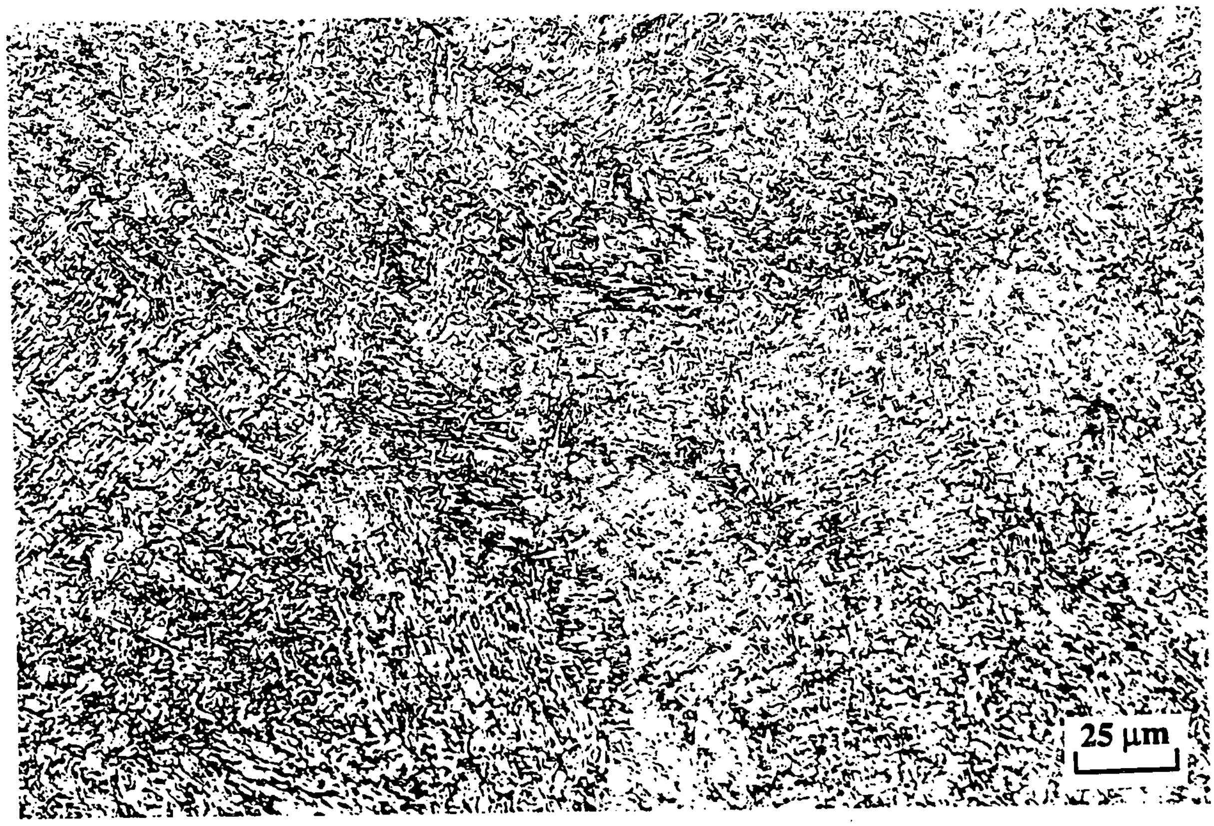


(b) microstructural constituents

Fig. 20. Optical micrographs showing as-deposited microstructure of GMA full thickness weld deposited at 2 kJ/mm in HSLA100 steel with the LTEC 120S1 and shielding gas.



(a) reheated structure



(b) microstructural constituents

Fig. 21. Optical micrographs showing reheated microstructure of GMA full thickness weld deposited at 2 kJ/mm in HSLA100 steel with the LTEC 120S1 and C20 shielding gas.

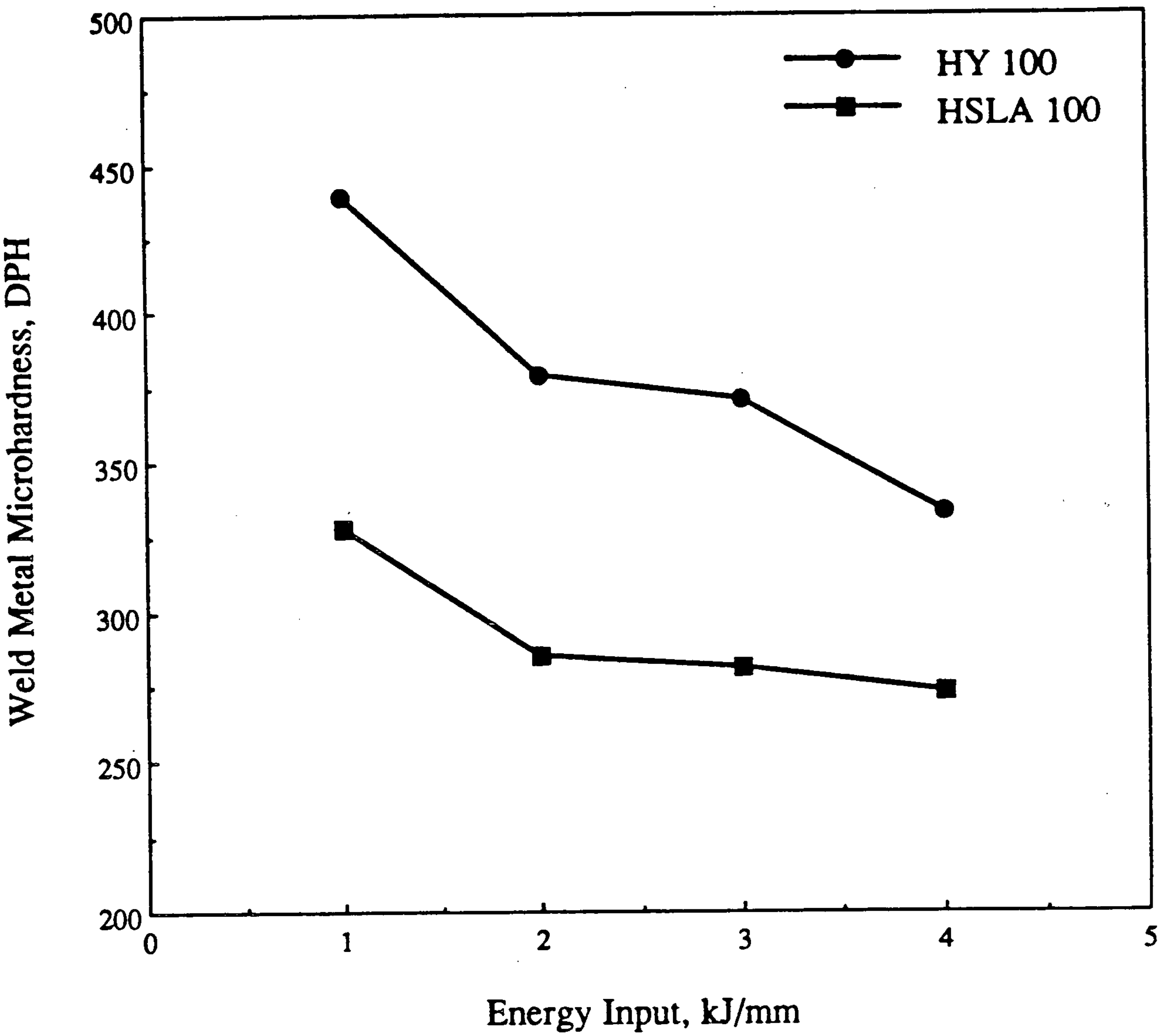


Fig. 22. Weld metal microhardness versus energy input for SA bead-in groove welds deposited in HSLA100 and HY100 steels with the LTEC 120S1 and OP121TT consumable combination.

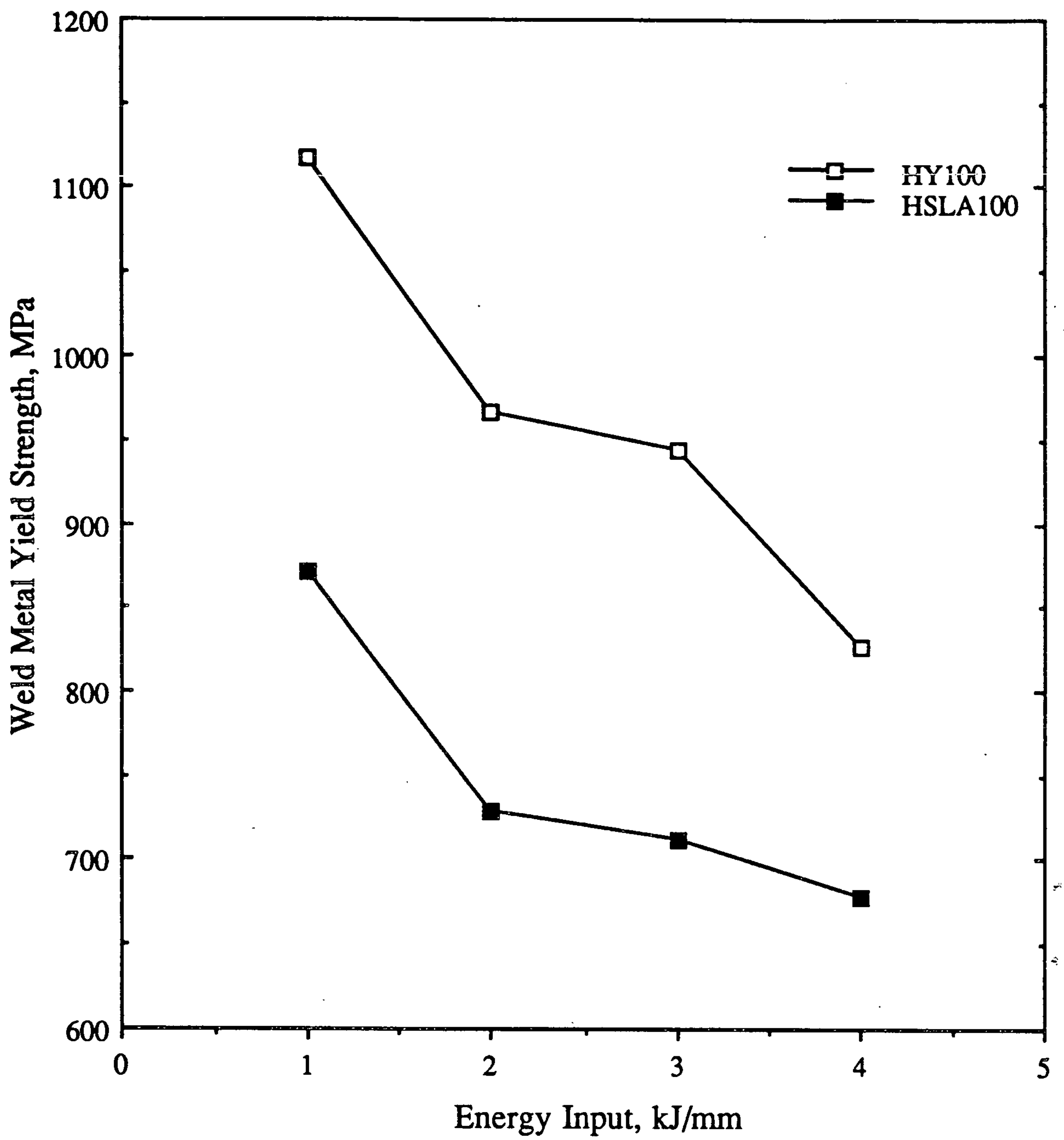


Fig. 23. Weld metal yield strength versus energy input for SA bead-in groove welds deposited in HSLA100 and HY100 steels with the LTEC 120S1 and OP121TT consumable combination.

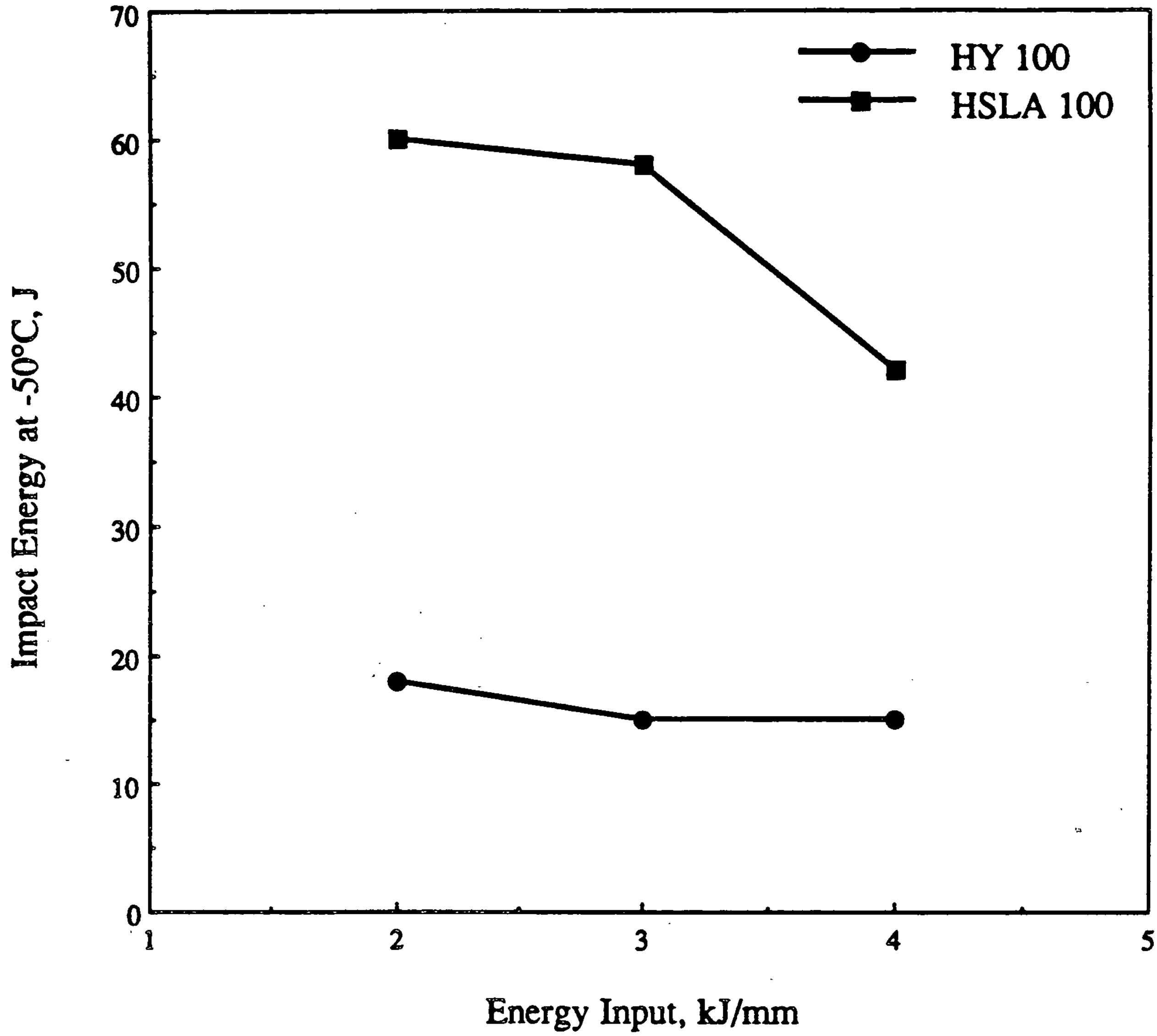


Fig. 24. Weld metal impact energy versus energy input for SA bead-in groove welds deposited in HSLA100 and HY100 steels with the LTEC 120S1 and OP121TT consumable combination.

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HSLA-100 Steel

High strength steels

Low alloy steels