Observations on welding of $\alpha_2 + O + \beta$ titanium aluminide

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The weldability characteristics of an $\alpha_2 + O + \beta$ titanium aluminide of nominal composition Ti–24Al–15·5Nb (at.-%) have been investigated. Conventional gas tungsten arc (GTA) and electron beam (EB) welds exhibited columnar fusion zone grains. Pulsed current and arc oscillated GTA welds exhibited predominantly equiaxed fusion zone grains. The microstructure of GTA welds and pulsed current GTA welds exhibited $\alpha_2 + O$ phases, whereas arc oscillated GTA welds and EB welds contained $\alpha_2 + O + \beta_0/\beta_2$; however, β_0/β_2 is predominant in EB welds. The EB welds, which contained $\alpha_2 + \beta_0/\beta_2$ microstructure, exhibited high strength and ductility compared with GTA welds. The observed microstructural variations are explained on the basis of possible weld thermal cycles and convective currents in the weld pool. STWJ/226

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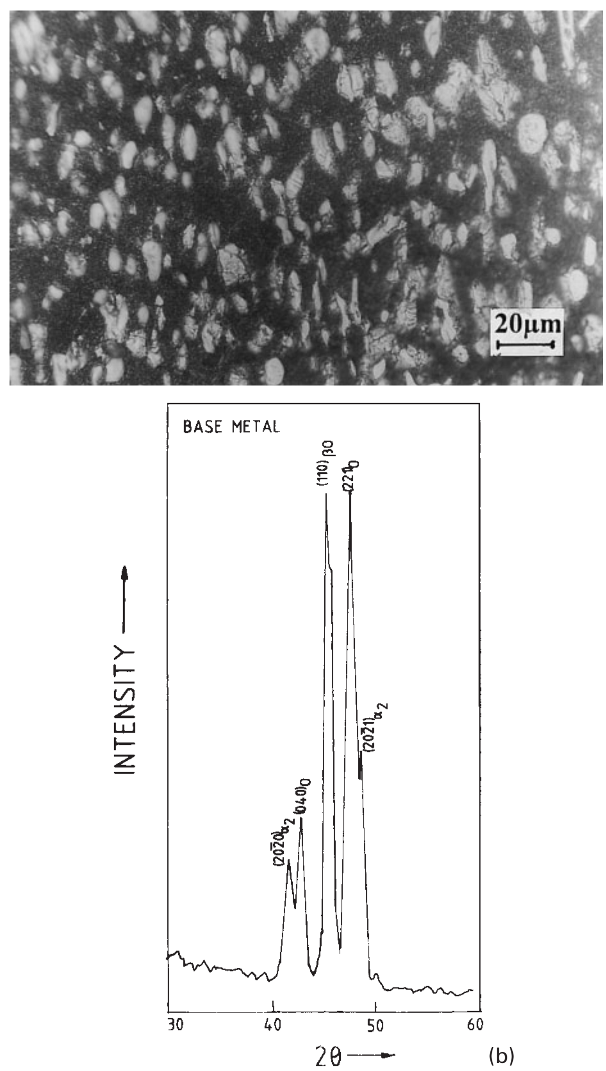
INTRODUCTION

Titanium aluminides have a density advantage over nickel base superalloys. Additionally, titanium aluminides exhibit superior creep strength,[1] although they lack room temperature ductility, which is a prerequisite for any engineering application in which safe design and ease of fabrication are required. Ductility improvements have been achieved by the addition of a β stabilising elements,[2] namely niobium. Addition of niobium at concentrations between 7·5 and 12 at.-% results in an $\alpha_2 + \beta$ microstructure. A further increase in Nb addition leads to orthorhombic (O) phase formation.[3,4] The presence of O phase imparts additional benefits with respect to creep properties. The majority of previous welding studies on α_2 titanium aluminides are confined to $\alpha_2 + \beta$ alloys.[5–12] These studies have indicated that cooling rates must be maintained below about 10 K s^{-1}, or be greater than 100 K s^{-1}, to achieve ductile welds. It was observed that at low cooling rates an $\alpha_2 + \beta$ structure is obtained, whereas at cooling rates of about 100 K s^{-1} a retained β structure is obtained. The presence of β phase leads to ductile welds. Intermediate cooling rates give fine acicular microstructures consisting of $\alpha_1 + \alpha_2'$. These microstructures lack ductility. Limited post-weld heat treatment (PWHT) studies indicated that a PWHT temperature as high as 980°C is required to improve the properties.[11] Welding studies on the $\alpha_2 + O + \beta$ class of alloys have not been reported to date. The present paper investigates the welding aspects of an $\alpha_2 + O + \beta$ alloy having the nominal composition Ti–24·5Al–15·5Nb (all compositions are in at.-%). The welding processes selected are gas tungsten arc (GTA) and electron beam (EB) welding. In GTA welding, novel welding techniques such as current pulsing and arc oscillation, which have not previously been reported in the literature with respect to titanium aluminide, also formed a part of the present study.

EXPERIMENTAL PROCEDURE

The alloy selected for the present study is an $\alpha_2 + O + \beta$ class of titanium aluminide of nominal composition Ti–24·5Al–15·5Nb (β transus 1125°C). The alloy was received in the form of 4 mm thickness sheet in the $\alpha_2 + \beta$ (980°C) rolled condition, with a starting microstructure consisting of primary equiaxed α_2 and acicular $\alpha_2 + \beta$ microstructure, as shown in Fig. 1. GTA welding and EB welding were



a optical microstructure; *b* X-ray diffraction, showing $\alpha_2 + \beta_0 + O$ phases

1 Microstructure of $\alpha_2 + \beta$ processed base metal

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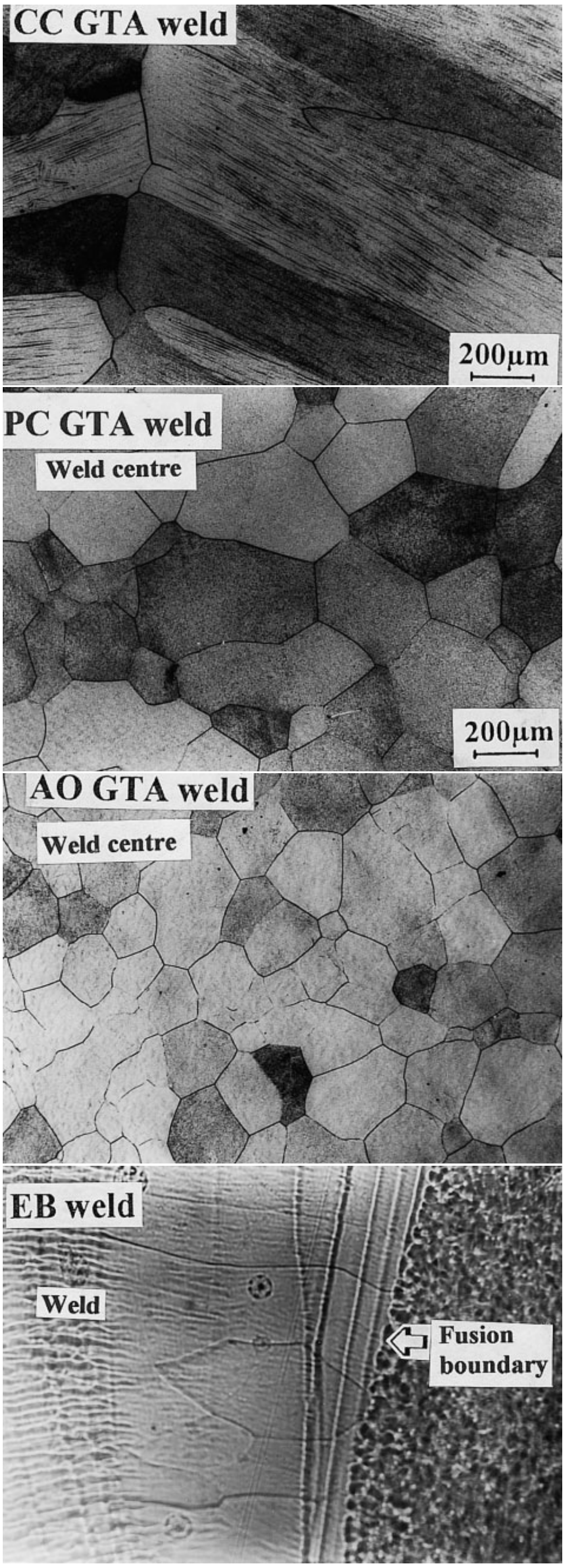
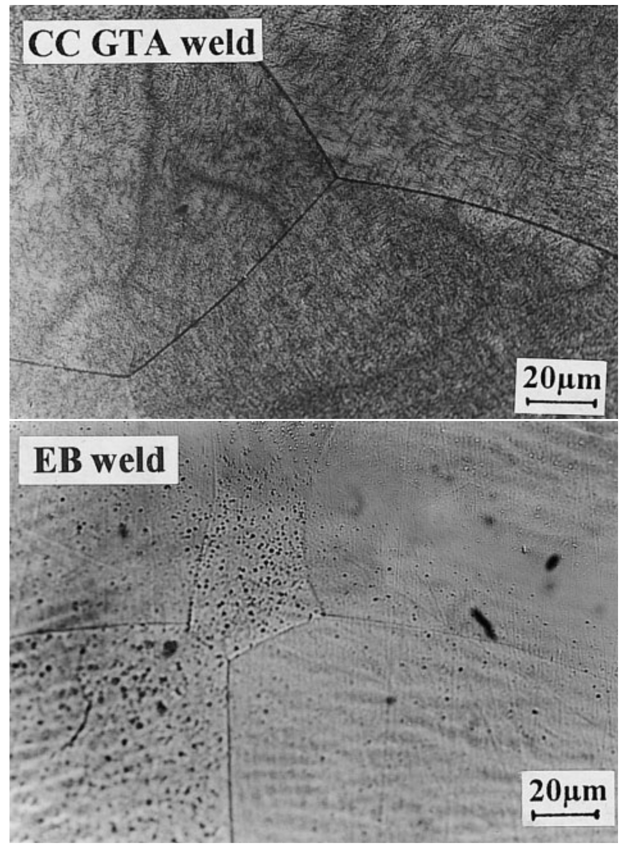


GTA gas tungsten arc; CC continuous current; PC pulsed current; AO arc oscillation; EB electron beam

2 Fusion zone grain structure of welds (optical)

employed. In GTA welding, novel techniques consisting of pulsed current (PC) application and arc oscillation (AO) were also included in the programme. The welding parameters for full penetration autogenous welds are presented in Table 1. The welds were characterised for microstructure, phases present, and mechanical properties. Microstructure examination was carried out using optical and scanning electron microscopes. Kroll's reagent was employed as an etchant. For the identification of the

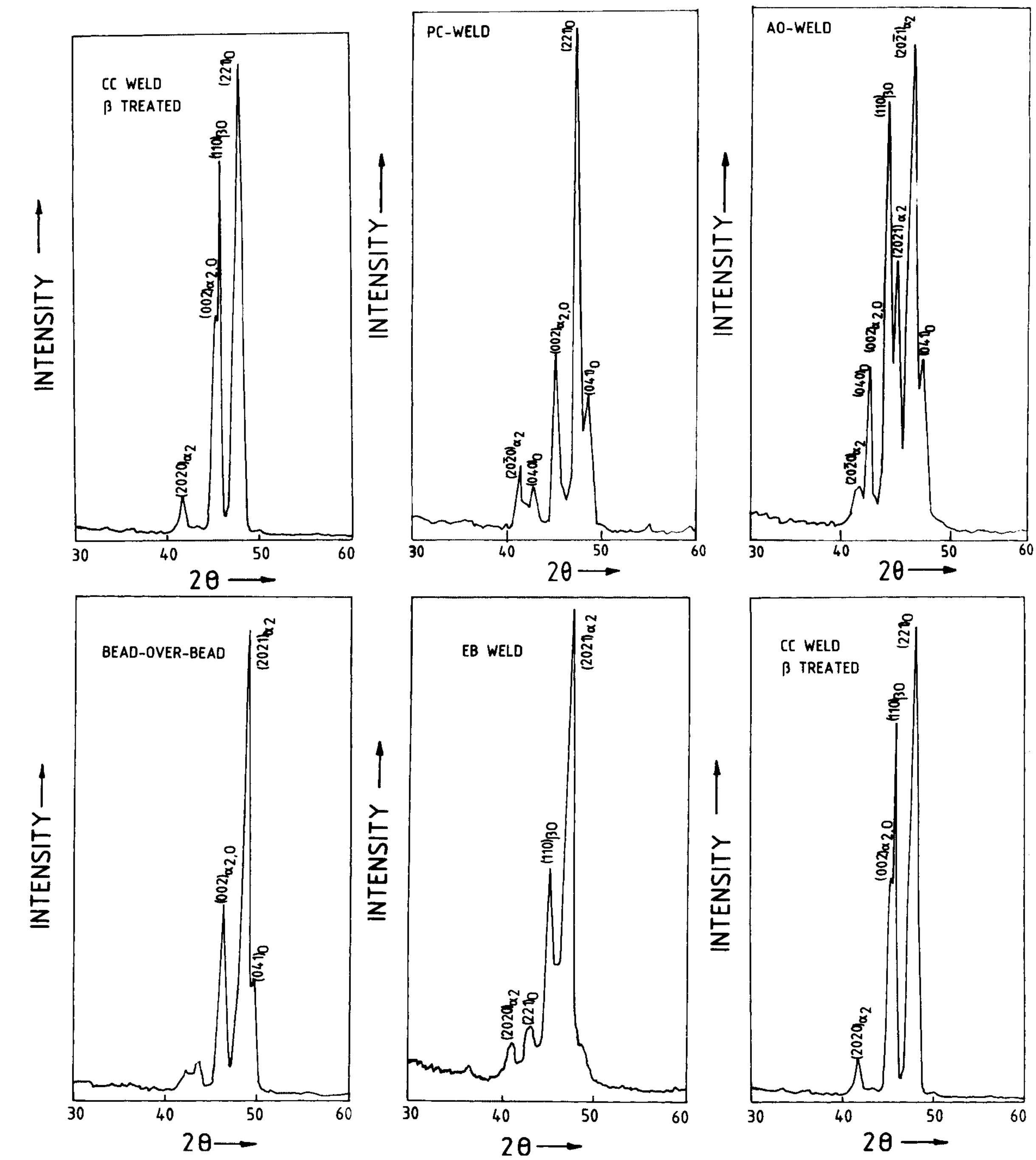


3 Microstructure of weld fusion zone (optical)

Table 1 Welding parameters

Process	Parameter	Value/characteristics
GTA welding, common	Electrode	2% thoriated tungsten
	Torch position	Vertical
	Polarity	Direct current straight
	Torch gas flowrate	7 L min^{-1}
	Purging gas flowrate	14 L min^{-1}
	Backing gas flowrate	5 L min^{-1}
	Arc voltage	16 V
GTA, CC mode	Welding current	230 A
	Welding speed	5 mm s^{-1}
GTA, AO mode	Welding current	250 A
	Oscillation frequency	10 Hz
	Oscillation amplitude	1 mm
GTA, PC mode	Welding speed	1·5 mm s^{-1}
	Peak current	300 A
	Base current	30 A
	Pulse on time/off time ratio	0·2
	Pulse frequency	2 Hz
EB welding	Beam voltage	100 kV
	Beam current	50 mA
	Welding speed	22 mm s^{-1}
	Gun to work distance	400 mm
	Vacuum pressure	10^{-5} torr

GTA gas tungsten arc; CC continuous current; AO arc oscillation; PC pulsed current; EB electron beam.



4 X-ray diffraction intensity data for various welding techniques investigated

phases present, X-ray diffraction using Mo K_α radiation was employed. Longitudinal tensile strength with the weld oriented along the loading axis was evaluated at a strain rate of 1×10^{-3} s^{-1}, employing standard tensile specimens. A Vickers hardness survey was also carried out. To ascertain the phases present, one of the welds was subjected to a post-weld β heat treatment.

RESULTS AND DISCUSSION

The microstructure of constant current (CC) GTA welds consists of a columnar grain structure. Introduction of PC and AO techniques results in a predominantly equiaxed grain structure, as can be seen in Fig. 2. The EB welds also consist of a columnar grain structure (Fig. 2). The transgranular microstructure in GTA welds consists of fine acicular product. Remelted (bead over bead) welds exhibited a coarser acicular product. In EB welds the transgranular microstructure is predominantly featureless although some evidence of precipitates is observed, as shown in Fig. 3. X-ray diffraction patterns indicated that all GTA welds, with the exception of arc welds, consist of α_2+O phase, whereas AO welds and EB welds consist of $\alpha_2+\beta/\beta_0$+O, as can be seen in Fig. 4 and Table 2. The β peak for the AO weld is weak. The predominant columnar grain structure in CC GTA welds and EB welds occurs as a consequence of epitaxial solidification due to the large thermal gradient between the fusion boundary and the weld pool. Introduction of current pulsing and arc oscillation leads to weld pool churning, favouring equiaxed grain formation. In addition, the convective currents can lead to dendrite fragmentation at the weld pool boundary. These fragments are distributed in the weld pool, providing a greater number of nucleation sites. This would lead to

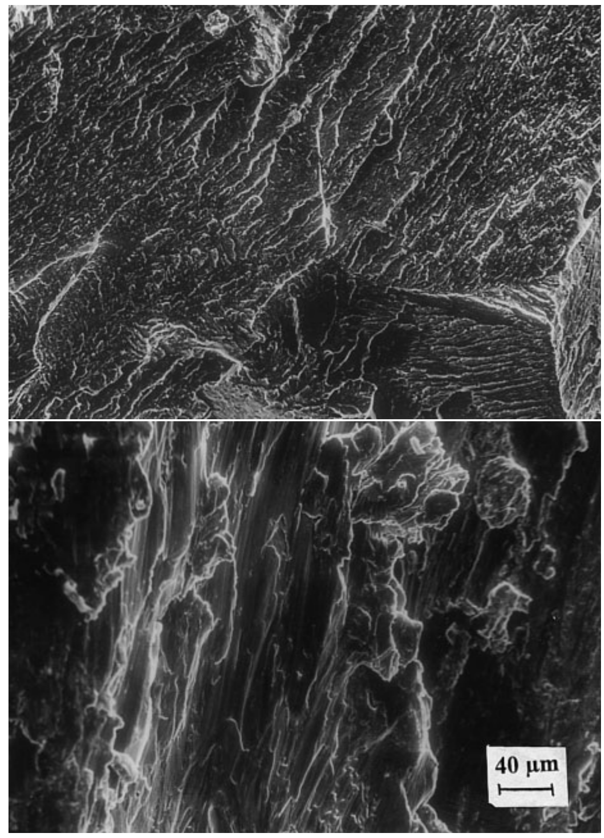
Table 2 Summary of various phases present in fusion zone of GTA and EB welds

Phase	CC weld	PC weld	AO weld	BOB weld	CC weld, β treated	EB weld
α_2	002	2020	2020	002	2020	2020
		002	2021	2021	002	2021
			002			
β_0	…	…	110	…	110	110
O	040	040	040	002	002	221
	002	002	002	041	221	
	041	221	041			
		041				

BOB bead on bead.

equiaxed grain formation. The tendency for equiaxed grain formation is expected to be greater in AO welds owing to the additional magnetic field introduced to produce arc oscillation. Predominant α_2+O formation in GTA welds is thought to be due to cooling rates that are insufficient to retain the high temperature β phase. The presence of β phase in AO welds could be due to greater cooling rates in such welds. The cooling rate has been verified to be >100 K s^{-1} by temperature measurement in the weld pool. The predominant presence of β phase in EB welds results from cooling rates >100 K s^{-1}. To ascertain the phases present in GTA welds, CC GTA welds were subjected to β treatment. The PWHT CC welds exhibited the presence of β phase (Fig. 4). This confirms that in CC and PC GTA welds cooling rates are not sufficiently low to attain a desirable two phase $\alpha_2+\beta$ microstructure.

The GTA welds exhibited higher hardness than the EB welds, as can be seen in Table 3. Among the GTA welds, PC and AO welds showed a reduction in hardness. Remelting of the weld pool via the bead over bead (BOB) technique also led to a reduction in hardness. The β heat treated CC GTA weld exhibited a hardness equivalent to that of the β heat treated base metal. All GTA welds exhibited very low strength and practically no ductility, although PC and AO welds showed marginally higher strength. The EB welds exhibited higher strength and ductility, comparable to those of the base metal (Table 3). The high hardness and low ductility of GTA welds is due to the fine acicular microstructure consisting of α_2+O, with the exception of AO welds which exhibited the presence of β phase. However, the β phase present in AO welds may not be sufficient to reduce the hardness and improve the ductility. The low hardness of EB welds is due to the presence of α_2+O+β, with the β phase predominating. The very low strength and ductility of GTA welds in spite of their high hardness can be attributed mainly to α_2+O phases. The EB welds, with a predominant presence of ductile β phase, exhibited high strength, probably due to the low notch sensitivity of β phase. The lower strength GTA welds exhibited cleavage fracture features, whereas EB welds, possessing higher strength, failed via ductile fracture, as shown in Fig. 5. In spite of the predominant presence of β phase the low ductility of EB welds, equivalent to that of $\alpha_2+\beta$ heat



5 Typical fractographs of longitudinal tensile specimens of *a* GTA weld and *b* EB weld (SEM)

treated base metal, can be attributed to a low volume fraction of weld metal due to the narrowness of EB welds.

CONCLUSIONS

Gas tungsten arc and electron beam welding of α_2+O+β titanium aluminides was carried out. The effect of current pulsing and arc oscillation has also been studied in GTA welds. Conventional GTA welds and electron beam welds exhibited columnar grains due to epitaxial solidification, whereas PC and AO GTA welds exhibited equiaxed grains. In general, GTA welds exhibited high hardness due to the presence of mainly α_2+O phases. In contrast, EB welds exhibited a hardness equivalent to that of the $\alpha+\beta$ heat treated base metal owing to the presence of α_2+O+β phases and a predominance of β phase. In general, GTA welds, consisting of mainly α_2+O, exhibited low strength and low ductility in spite of their high hardness, possibly as a result of the high notch sensitivity of this microstructure. The EB welds, containing α_2+O+β phases, exhibited a high strength, greater than that of the base metal in the $\alpha_2+\beta$ rolled condition. However, the ductility of EB welds is nearly equal to that of the $\alpha_2+\beta$ rolled base metal,

Table 3 Longitudinal (all weld metal) tensile properties and fusion zone hardness of welds

Type of weld	Ultimate tensile strength, MPa	Yield strength, MPa	Elongation, %	Fusion zone hardness, HV0·5
Base metal, β treated	950	820	3·2	300
Base metal, $\alpha_2+\beta$ rolled	600	550	2	320
CC weld	200	…	<1	560
PC weld	260	…	<1	475
AO weld	300	250	<1	450
BOB weld	200	…	<1	490
EB weld	773	700	2	350

possibly as a result of the low volume fraction of weld region that is characteristic of narrow EB welds.

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