



The application of model-based processing diagrams to electron beam welding of Ti-6Al-4V

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Abstract

Electron beam welding is a high efficiency joining technology used in a range of industries to achieve high integrity welds. Model-based processing diagrams for laser treatment of engineering materials have been previously developed and have the potential to assist with the rapid selection of appropriate welding parameters. This paper investigates whether such a model-based approach for laser welding can be applied to electron beam welding and used for the rapid selection of workable processing parameters. Trials were performed on 4.7 mm thick plate and the selected welding parameter combinations led to a through-thickness weld with satisfactory mechanical performance. Such model-based diagrams are straightforward to construct and can reduce early-stage research and development costs.

Keywords

electron beam welding, processing diagrams, microstructure, titanium alloys, mechanical properties

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Introduction

Laser and electron beam welding are high efficiency joining and repair technologies used in a range of industries including the automotive and aerospace sectors.^{1,2} The high power-densities associated with these two technologies lead to the surface temperature of the alloy being processed to exceed its boiling point, thus forming a deeply penetrating vapour cavity or “keyhole”,³ which allows relatively thick sections of metals and alloys to be bonded together with a high-integrity weld. In contrast to manual techniques such as Tungsten Inert Gas welding, laser and electron beam weldments yield a fine microstructure within the fusion zone,⁴ which may result in the local mechanical properties being superior to that of the work-piece material.

A key challenge for scientists and engineers who employ laser and/or electron beam welding technologies for industrial applications, is the selection of appropriate beam power and velocity combinations to achieve a fully penetrating weld with acceptable mechanical integrity. This is potentially a lengthy process, especially if the machine platform operatives have little or no prior experience in working with a particular alloy system, as series of welding trials investigating the effect of beam power and traverse rate will need to be performed. For example, Squillace et al.⁵ studied a range of powers and velocities between 800–1200 W and $17\text{--}28 \times 10^3$ m/s, respectively for laser welding of 1 mm Ti-6Al-4 V plate, whilst Ahn et al.⁶ undertook a comprehensive parametric study to investigate the effect of laser beam power, velocity and focal position on the microstructure and weld quality of 2 mm-thick fibre laser welded joints.

In an attempt to reduce the number of trials required, model-based processing diagrams for laser treatment of engineering materials have been developed by Ion et al.³ Here, analytical heat flow models were applied to identify dimensionless groups of processing and material parameters. These dimensionless descriptors can be used to identify a process window, which is (somewhat) agnostic in terms of both the alloy and laser beam used. A description of the procedure used to construct such diagrams is presented in Section 2. These processing diagrams have the potential to aid engineers in the selection of appropriate welding parameter combinations to achieve a desired depth of treatment during laser processing and have been adapted and successfully applied to powder bed fusion technologies.^{7,8} The model-based approach described by Ion et al.,³ has also shown promise for the initial down selection of electron beam processing parameters during limited “bead-on-plate” welding trials for joining dissimilar materials using an electron beam powder bed fusion platform.⁹ However, to the best of the authors’ knowledge, the applicability of these

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Table 1. Summary of selected laser and electron beam welding process parameters for Ti-6Al-4 V reported in the literature. Thermophysical property data for Ti-6Al-4 V were taken from Ref.¹⁷

	Heat source (type)	Workpiece Thickness, l m	Normalized Plate Thickness, l^* -	Power, q W	Velocity, v m/s	Normalised Power, q^* -	Normalised Beam Velocity, v^* -
Cao et al. (2009) ¹¹	Laser Beam	$1 \text{ \& } 2 \times 10^{-3}$	4.4 & 8.9	2500	$75\text{--}175 \times 10^{-3}$	304	5.9–13.7
Squillace et al. (2012) ⁵	(Nd:YAG) Laser Beam	1.6×10^{-3}	8	800–1200	$17\text{--}58 \times 10^{-3}$	110–164	1.2–4
Xu et al. (2014) ¹²	(Nd:YAG) Laser Beam	6×10^{-3}	6	6000	$23\text{--}33 \times 10^{-3}$	164	8.1–11.6
Ahn et al. (2016) ⁶	(CO ₂) Laser Beam	2×10^{-3}	6.2	2500	50×10^{-3}	211	5.6
Rominini et al. (2023) ¹³	(Yb-fibre) Laser Beam	3×10^{-3}	25	2800	$17\text{--}67 \times 10^{-3}$	639	0.7–2.8
Tsai et al. (2014) ¹⁴	(CO ₂) Electron Beam	3×10^{-3}	6	3000	25.3×10^{-3}	274	4.4
Wang et al. (2012) ¹⁵	Electron Beam	6×10^{-3}	12	1800–3000	$5\text{--}15 \times 10^{-3}$	164–274	0.9–2.6
Saresh et al. (2007) ⁴	Electron Beam	21×10^{-3}	42	10500	21×10^{-3}	959	3.7
Xu et al. (2022) ¹⁶	Electron Beam	3×10^{-3}	6	2550	13×10^{-3}	233	2.3

dimensionless groups to industry standard electron beam welding equipment has not been reported.

Thus, the aim of this study is to investigate whether such a model-based approach for laser welding of engineering materials can be directly applied to large-scale electron beam welding platforms and used for the rapid selection of processing parameters to achieve a through-thickness weld of satisfactory mechanical strength. To achieve this, patch insert welding trials were performed on 4.7 mm thick Ti-6Al-4 V plate and the electron beam welding parameters were selected based on the theoretical values of beam power (q) required to achieve a fully penetrating weld for a given beam velocity (v) and plate thickness (l). The mechanical integrity of the patch welds was evaluated by microhardness mapping and quasi-static tensile testing, and microstructural characterisation was performed using light microscopy and scanning electron microscopy. Finally, the tensile test results obtained in this study are compared with tensile data for Ti-6Al-4 V manufactured and welded via a range of industrial processes.

Model-based processing diagrams for laser and electron beam welding

For the case of laser treatment of engineering materials, Ion et al. define the following two dimensionless groups of processing and material variables:³

The dimensionless beam power:

$$q^* = A \cdot q / [r_B \cdot \lambda (T_m - T_0)] \quad (1)$$

The dimensionless beam velocity (or traverse rate):

$$v^* = v \cdot r_B / \alpha \quad (2)$$

Where A is the surface absorptivity (or coupling coefficient) and ranges between 0.3 and 0.8 depending on process and heat transfer mechanism (See Table 1 in Ref.³), r_B is the beam radius, λ and α are the thermal conductivity and thermal diffusivity of the alloy being processed, whilst T_m and T_0 are the respective melting and initial temperatures of the material to be treated.

For keyhole welding conditions, where the peak surface temperature reaches the boiling point of the material being treated, Ion et al.³ provide a heat balance between the absorbed power and the power expended by vaporisation, melting and conduction which results in the following dimensionless equation:

$$q^* = l^* v^* L_v^* + [(l^{*2} v^* L_m^*)/4] + (2\pi l^* / \ln(8)) \quad (3)$$

Here, the dimensionless treatment depth, l^* , is equal to l/r_B , whilst L_v^* and L_m^* are the normalised latent heat of vaporisation and the dimensionless volumetric latent head of melting, and are approximately 3.9 and 0.39 for metals and alloys respectively.^{3,10}

To construct a model-based processing diagram for laser and electron beam welding of Ti-6Al-4 V, processing parameter data for laser beam^{5,6,11–13} and electron beam^{4,14–16} welding of Ti-6Al-4 V were collected from the scientific literature. Processing parameter data included beam power (q), velocity (v), radius (r_B) and workpiece thickness (l), and are listed in Table 1. For each study, the corresponding dimensionless beam power (q^*) and beam velocity (v^*) were calculated using Equations 1 and 2, respectively. Thermophysical property data for Ti-6Al-4 V, including density, liquidus, thermal conductivity and specific heat capacity were taken from Ref.¹⁷ The coupling coefficient, A , in Equation 1 was assumed to be 0.3 and 0.5 for the case of laser and electron

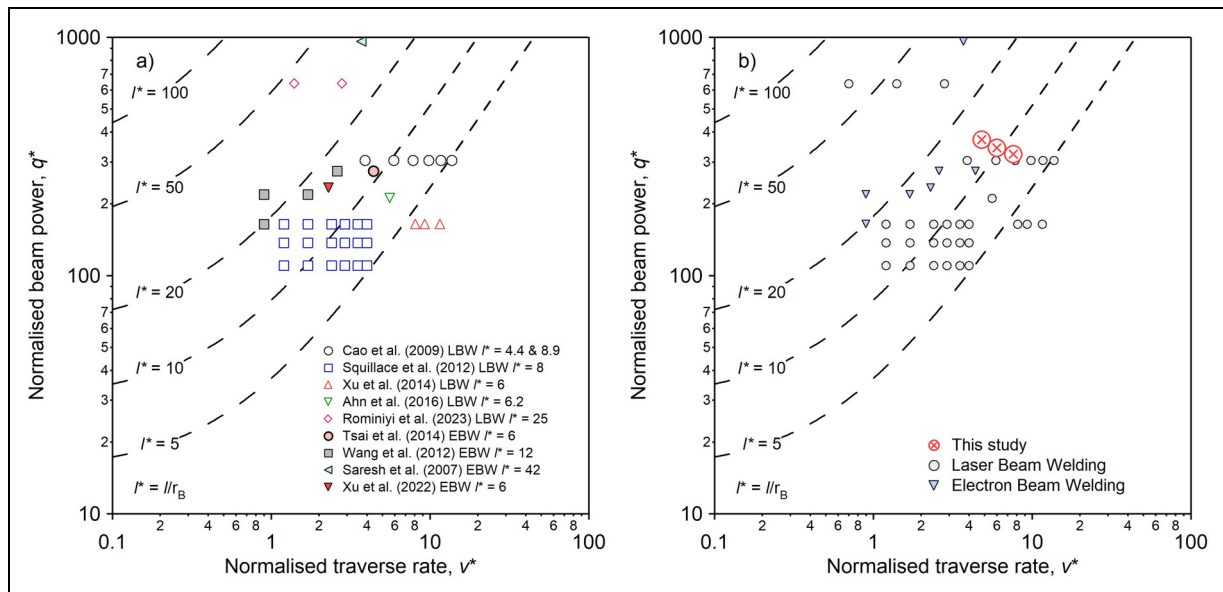


Figure 1. a) Normalised model-based processing diagram constructed from equations 1–3 and using the welding parameter data for Ti-6Al-4 V listed in Table 1. Isopleths of l^* represent the theoretical minimum normalised power required to achieve a fully penetrating weld for a given dimensionless plate thickness, l^* and dimensionless velocity, v^* . The location of the dimensionless power (q^*) and velocity (v^*) combinations used for the 4.7 mm-thick Ti-6Al-4 V patch insert welds are provided in b) and are indicated by the red markers. LBW = Laser beam welding and EBW = Electron beam welding. Note that the terms q^* and v^* are dimensionless numbers. Adapted from Ref.³

Table 2. List of electron beam welding parameters investigated for the Ti-6Al-4 V patch insert welds. Plate thickness = 4.7 mm (dimensionless thickness, $l^* = 9.4$).

Welding Trial Number	Beam Power, q W	q^* -	Beam Velocity, v m/s	v^* -	q/v kJ/m	q^*/v^* -	Comment
1	4070	372	0.027	4.8	150.7	78	“High-energy”
2	3770	344	0.035	6.0	107.7	57	“Medium-energy”
3	3540	323	0.044	7.6	80.4	43	“Low-energy”

beam welding, respectively.^{18,19} The dimensionless values for beam power (q^*) and beam velocity (v^*) are presented in the form of a model-based processing diagram in Figure 1 a). Superimposed onto Figure 1 are isopleths of the dimensionless depth of treatment, l^* , calculated using Equation 3. The dimensionless depth (l^*) represents the theoretical maximum thickness of plate that can be welded for any combination of normalised beam power (q^*) and velocity (v^*). For example, a plate of 5 mm thickness being treated with a laser beam of radius 250 μm would have a dimensionless plate thickness of $l^* = 20$. Thus, if the normalised velocity from Equation 2 is determined to be $v^* = 2$, then a dimensionless beam power of $q^* = 300$ would be required to achieve a depth of treatment corresponding to the thickness of the plate and therefore obtain a fully penetrating weld.

To test the applicability of the model-based approach described above, electron beam welding trials were performed on Ti-6Al-4 V plate of thickness 4.7 mm. Taking the electron beam radius (r_B) to be approximately 0.5×10^{-3} m, this plate thickness corresponds to a required dimensionless treatment depth (l^*) of 9.4. For such a treatment depth and taking the dimensionless velocity to be $v^* = 6$, a dimensionless beam power of $q^* \sim 300$ would be required to achieve a fully penetrating weld. The welding parameters investigated in this study, namely beam power (q) and beam

velocity (v), are listed in Table 2, alongside the corresponding dimensionless values for beam power (q^*) and velocity (v^*). Their locations in the normalised model-based processing space are also indicated graphically by red markers in Figure 1 b). Three welding parameter combinations were investigated: Namely a low-, medium- and high-energy condition, which correspond to dimensionless line energies (q^*/v^*) of 43, 57 and 78 (see Table 2). For a dimensionless treatment depth of $l^* = 9.4$, the normalised beam power (q^*) and velocity (v^*) combinations used in the case of the medium- and high-energy situations were greater than the theoretical value required to achieve a fully penetrating weld. On the other hand, the normalised beam power (q^*) and velocity (v^*) combination used in the low-energy condition falls slightly below the theoretical threshold required for a through thickness weld.

Experimental methods

Starting materials

Wrought Ti-6Al-4 V plate of thickness 4.7 mm (by 250 mm by 150 mm) was annealed above the β -transus temperature for Ti-6Al-4 V and slow cooled. This procedure was followed to simulate the microstructure of cast Ti-6Al-4 V, which was the material condition used in the industrial

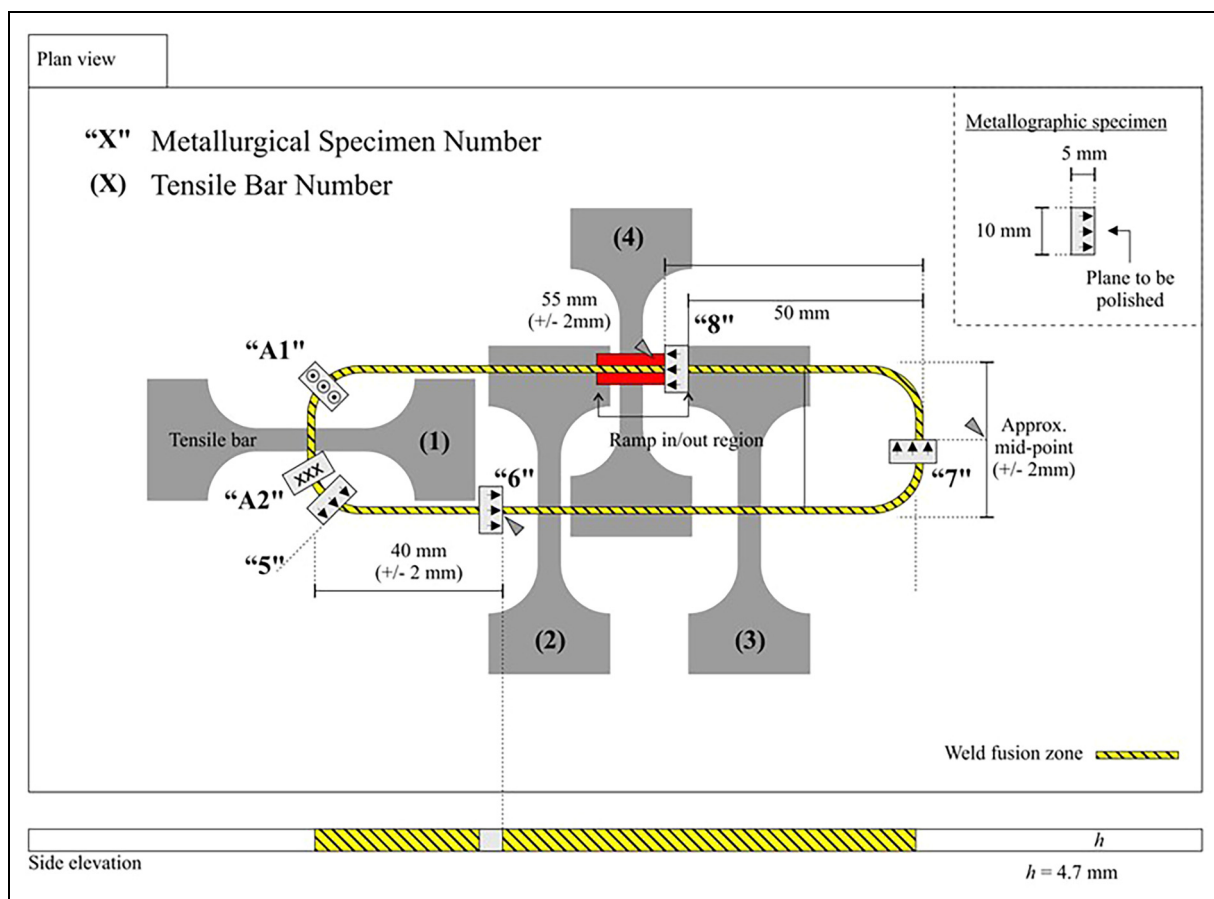


Figure 2. Schematic diagram of the patch weld arrangement illustrating the locations from which the tensile test bars and metallography specimens were harvested. Patch insert dimensions are length = 130 mm, width = 30 mm, thickness = 4.7 and corner radius = 10 mm.

application related to this study. Through thickness holes with geometry consisting of a rounded rectangle of nominal length = 130 mm, width = 30 mm and corner radius = 10 mm were machined from the centre of the plate. A schematic drawing of the rectangular plates used in this study is given in Figure 2. Patch repair inserts were machined from similar Ti-6Al-4 V plate subjected to identical heat treatment (4.7 mm thickness) with the same outer geometry as the hole. To allow the patch to be inserted they were cooled with liquid nitrogen and freeze-fit into position to replicate a patch weld repair on an aerospace gas turbine engine compressor casing. This process results in the patch being self-supporting in the required location and avoids the need for any additional clamping or fixtures.

Electron beam welding trials

Electron beam welding trials were carried out on a Pro-Beam K25 electron beam welding chamber with an accelerating voltage of 60 kV, a beam current ranging between 58.9 mA (for the low-energy condition) and 67.9 mA (for the high-energy condition), and a working distance of 450 mm. Three welding trials were performed in this study and the corresponding values for electron beam power and beam velocity are listed in Table 2. The dimensionless values for beam power (q^*) and velocity (v^*) were calculated using the procedure outlined in Section 2. During welding, the working chamber pressure was held between 1.4×10^{-4}

and 1.8×10^{-3} mbar, and no filler material was used. Post-weld heat treatments were not performed on the electron beam welds, and the microstructure and mechanical properties of the patch inserts were assessed in the as-welded condition.

Microstructural analysis and hardness testing

To assess the integrity and microstructure of the welds, metallographic specimens of the weld cross sections were harvested from the patch inserts using electrical discharge machining. The position from which the metallographic specimens were harvested is indicated in Figure 2. Harvested specimens were sectioned using a low-speed precision cut-off wheel, hot mounted in Bakelite and prepared for metallurgical analysis as follows: Samples were initially planar ground using water-lubricated SiC papers of sequentially increasing grit numbers. Fine grinding was conducted using a 9 μ m diamond suspension before final polishing using a colloidal silica suspension to generate a mirror finish suitable for microstructural analysis. Microstructural analysis was performed using both light microscopy and scanning electron microscopy. Prior to optical microscopy the samples were etched with Kroll's reagent. An FEI Magellan 400L SEM was used to gather high magnification backscattered electron micrographs, taken at the following approximate distances from the weld centreline: i) 0 mm (centreline), ii) 400 mm, iii) 800 mm, iv) 1200 mm and v) 1600 mm (base material).

Hardness testing was performed using a Struers Durascan automated hardness testing instrument using a Vickers indenter and a load of 0.1 kg. Approximately 1900 indent measurements were made across a region of 3 mm×5 mm per weld specimen, with a minimum spacing between hardness indents of 0.05 mm. To reduce noise arising from non-indexed indentations, a median filter was applied before plotting the hardness maps.

Mechanical testing

To measure the tensile properties of the electron beam welds, cross-weld tensile test pieces (width = 5.0 mm, thickness = 4.0 mm and gauge length = 24.0 ± 0.1 mm) were harvested from four locations across the patch welded plates. The locations from which the tensile test pieces were harvested from the patch welded plate are also shown in Figure 2. Tensile tests were performed at ambient temperature in laboratory air and in accordance with the testing standard BS EN 2002–1. Tests were performed under strain-controlled conditions (strain-rate of 0.002 min^{-1}) until the 0.2% proof strength was achieved, at which point the extensometer was removed and testing proceeded under displacement-controlled conditions (rate of 0.1 min^{-1}) until failure occurred.

Results and discussion

Macrographs of the high-, medium- and low-energy electron beam patch welds are shown in Figure 3. The weld fusion zone is roughly delineated by dashed lines and all three parameter combinations led to a fully penetrating weld. The fusion zone width is related to the dimensionless line energy (q^*/v^*), with the high-energy weld having a mid-height fusion zone width of approximately 2.4 mm, whilst this decreased to 1.2 mm for the low energy condition. The observed relationship between fusion zone width and dimensionless line energy is to be expected and aligns with the work of Ahn et al.⁶ for laser beam welding, who reported an increase in the measured weld top width from approximately 2.0 mm to 2.9 mm as the laser beam power was increased from 1.2 kW to 2.4 kW. In all cases the weld centreline can be observed and the fusion zone contains coarse, prior- β grains with a fine $\beta \rightarrow \alpha$ transformation product as shown in Figure 4 a) - d). The coarser, lamella-type microstructure of the β -annealed and slow cooled work-piece material adjacent to the fusion zone is shown in Figure 4 e). The fine microstructures observed in Figure 4 a) to d) are associated with rapid cooling through the β -transus and are comparable to the microstructures reported for water-quenched Ti-6Al-4 V (see for example Figure 1.a) in Ref.²⁰). A discussion about whether the fine microstructure observed within the fusion zone is martensitic or of the basketweave-type is beyond the scope of this study and in the absence of TEM and/or XRD studies no further conclusions will be drawn. Nevertheless, electron beam welding leads to a fine $\beta \rightarrow \alpha$ transformation product within the fusion zone, which should lead to enhanced quasi-static mechanical properties when compared with lower power-density welding technologies.

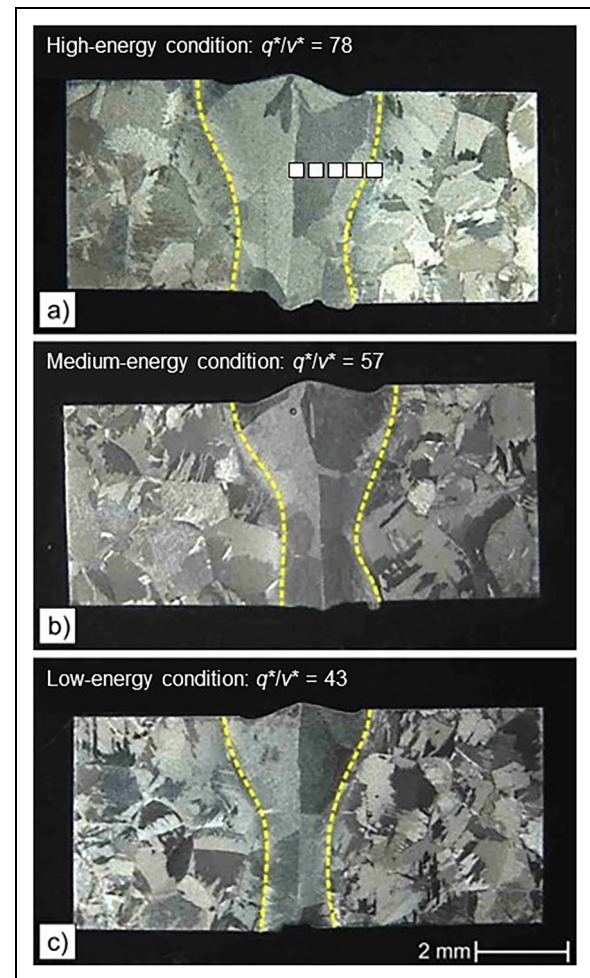


Figure 3. Light micrographs of a cross-section through the a) high-energy, b) medium-energy and c) low-energy Ti-6Al-4 V electron beam patch welds. The dimensionless line energy for each weld, q^*/v^* , is also indicated. The approximate boundaries of the weld fusion zone are marked by a dashed line.

Microhardness maps of the low-, medium- and high-energy patch welds are shown in Figure 5. The colour scale bar represents the magnitude of the local median Vickers hardness number (VHN) with blue corresponding to VHN values less than $300 \text{ HV}_{0.1}$ and yellow greater than $350 \text{ HV}_{0.1}$. As expected from Figures 3 and 4, the work-piece material has a considerably lower hardness than the weld fusion zone, with data generally falling in the range $280\text{--}320 \text{ HV}_{0.1}$. A few regions of higher hardness exist within the work-piece material however, and are potentially large colonies of similarly orientated α -laths whose crystallographic $\langle c \rangle$ -axis orientation is close to that of the indentation direction i.e., so-called “hard orientations”.²¹ In all cases, the hardness of the fusion zone is greater than that of the work-piece material and falls in the range $350\text{--}400 \text{ HV}_{0.1}$, which aligns with literature data for electron beam welding.¹⁵ The limited data available suggests that data collected from the low- and medium-energy conditions generally sit towards the upper end of the hardness spectrum. It is hypothesised that this increase is due to a finer $\beta \rightarrow \alpha$ transformation product in these welds compared with the high-energy welding parameters, although no attempt has been made to quantify the variation in the scale of the fusion zone microstructure.

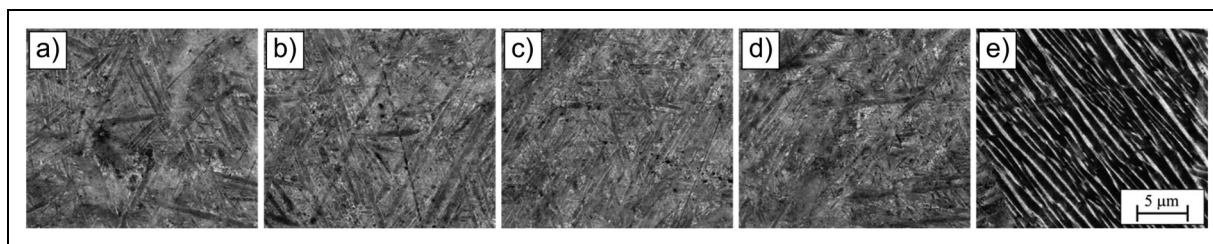


Figure 4. Backscatter electron micrographs showing the fine microstructure in the weld fusion zone (a-d) and the coarser lamellar structure in the base material (e). The position of the electron micrographs with respect to the weld centreline is indicated by white boxes running from left to right in Figure 3 a).

within this study. The microhardness mapping data also suggest that the general width of weld fusion zone is greater in the high-energy condition, which is consistent with the observations from Figure 3.

Quasi-static tensile mechanical property data for all the patch welds are listed in Table 3. The data is also plotted graphically in Figure 6, where it is compared with literature values for Ti-6Al-4 V^{13–15,22} manufactured and welded via a range of processes. Four tensile tests were performed on each

patch welded plate and the variation in yield strength between the three welding conditions is not statistically significant: The mean 0.2% proof strengths (to 95% confidence intervals) for the high-, medium- and low-energy conditions were calculated to be 834 ± 16.5 MPa, 830 ± 7.1 MPa and 843 ± 7.1 MPa, respectively. Visual examination of the fractured test bars indicated that failure had occurred away from the weld fusion zone and that the mechanical performance of the patch welds is instead controlled by the microstructure and composition of the work-piece material rather than the electron beam welded joint. Similar observations were made by Tsai and Wang,¹⁴ who reported that tensile fracture occurred either in the base material or within the heat-affected zone of electron beam welded Ti-6Al-4 V plate. Comparison with tensile data from the literature (Figure 6) supports this argument as the ultimate tensile strength and ductility data obtained in this study fall close to the tensile property data for cast Ti-6Al-4 V reported by Guo et al.²² It should be noted that the tensile data reported by Tsai and Wang¹⁴ and Wang and Wu¹⁵ in Figure 6 were obtained from electron beam welds performed on wrought Ti-6Al-4 V plate with a starting microstructure consisting of fine, equiaxed alpha grains of approximately 5 to 10 μm diameter.

All three dimensionless line energy (q^*/v^*) combinations led to a through-thickness electron beam weld with satisfactory mechanical integrity. This is perhaps somewhat unexpected since the normalised beam power (q^*) corresponding to the “low-energy” condition falls below the theoretical

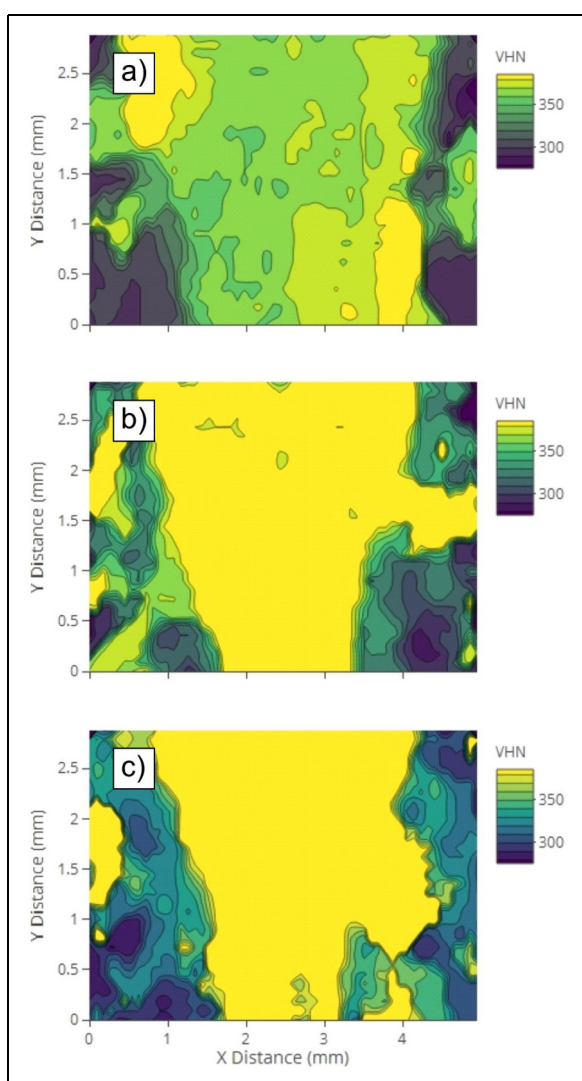


Figure 5. Vickers hardness number (VHN) maps (load of 0.1 kg.f ($HV_{0.1}$)) of the a) high-energy, b) medium-energy and c) low-energy Ti-6Al-4 V electron beam patch welds. The direction of beam travel is normal to the plane of the page.

Table 3. Tensile properties of the electron beam welded Ti-6Al-4 V patch inserts investigated in this study. Testing was performed in accordance with BS EN 2002-1.

Welding Trial Number	Comment	0.2% Proof Stress MPa	Ultimate Tensile Strength MPa	% Elongation
1	“High-energy”	814	961	6.1
1	“High-energy”	843	945	6.3
1	“High-energy”	852	950	5.8
1	“High-energy”	827	925	5.7
2	“Medium-energy”	836	936	6.1
2	“Medium-energy”	823	919	5.3
2	“Medium-energy”	824	918	6
2	“Medium-energy”	836	925	6.5
3	“Low-energy”	845	959	7.1
3	“Low-energy”	840	944	5.6
3	“Low-energy”	851	952	4.9
3	“Low-energy”	834	936	5.4

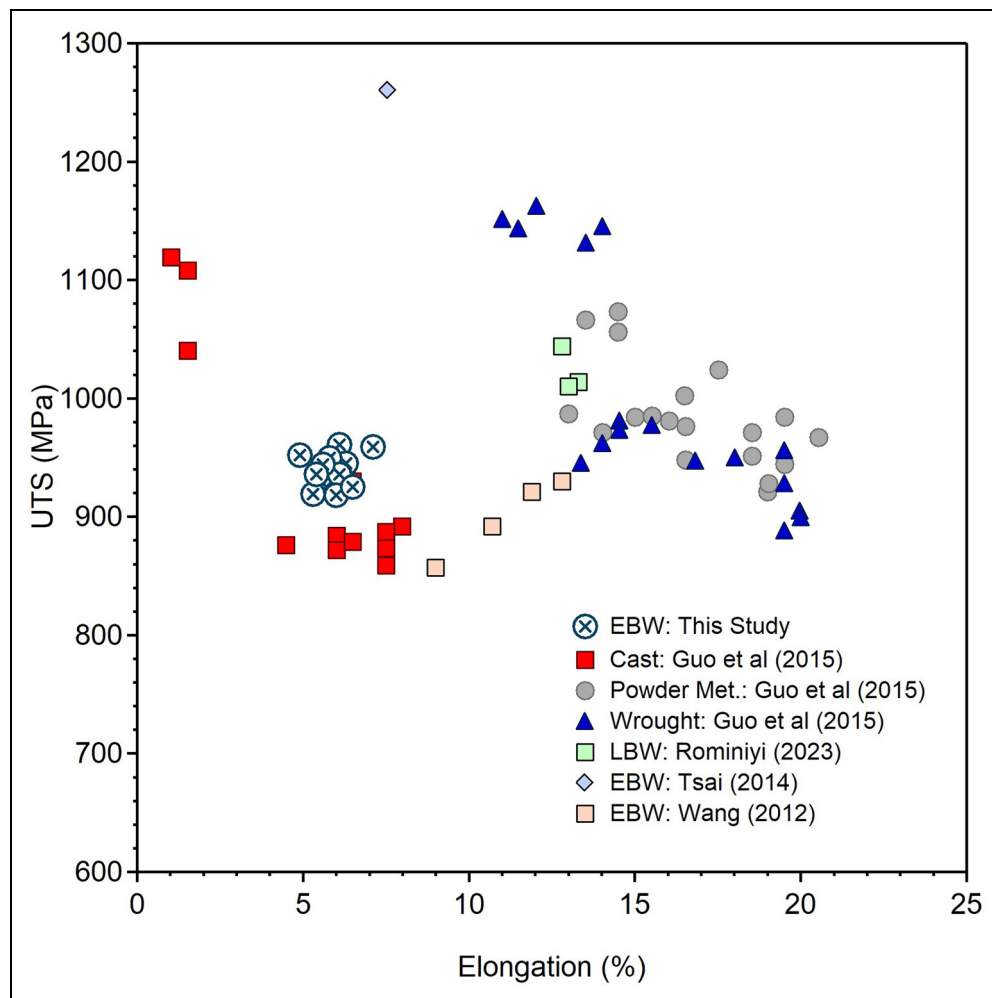


Figure 6. Ultimate tensile strength versus % elongation to failure for Ti-6Al-4 V manufactured and welded via a range of processes.^{13–15,22} the tensile properties of electron beam welded ti-6Al-4 V from this study are included for comparison. Note: Only the as-welded tensile data from Tsai (2014) is included here.

minimum required for a dimensionless plate thickness of $l^* = 9.4$ (Figure 1). This might be explained by the selection of a coupling coefficient of $A = 0.5$ during the design of these experiments, which is lower than the value reported for key-hole welding by Ion et al.,³ but nevertheless similar to that reported by White and Bakish.¹⁹ A drawback of this model-based approach to both laser and electron beam welding is the number of assumptions that need to be made when constructing the normalised processing parameter diagrams; the coupling coefficient, A , will have an impact on calculated values for dimensionless power as would the assumed thermo-physical properties of the material being welded. Notwithstanding their limitations however, these model-based diagrams are straightforward to construct using spreadsheet software and data available in the literature, and can rapidly provide development engineers with indicative values of the necessary parameters required to achieve an acceptable weld. This will minimise the number of pre-production welding trials that need to be performed, thus reducing material waste and early-stage R&D cost.

Conclusions

In this study, electron beam welding trials were performed on 4.7 mm thick Ti-6Al-4 V plate in the β -annealed condition.

The welding parameters, namely beam power (q) and velocity (v), were selected based on their proximity to the theoretical value required to achieve a fully penetrating weld using a model-based framework for laser processing developed by Ion et al.³ The following electron beam welding parameters (q/v) were investigated: 150.7 kJ/m (high-energy condition), 107.7 kJ/m (medium-energy condition) and 80.4 kJ/m (low-energy condition), which correspond to dimensionless line energies of $q^*/v^* = 78$, 57 and 43, respectively. From this research, the following conclusions are drawn:

- All three processing parameter combinations led to a fully penetrating weld. This indicates that the model-based framework originally developed for laser treatment of engineering materials can be successfully applied to electron beam welding and therefore used for the rapid selection of workable electron beam welding parameters.

Four tensile tests were performed on each of the high, medium and low-energy welds and in all cases, tensile fracture occurred away from the fusion zone. The mean 0.2% proof strengths (to 95% confidence intervals) for the high-, medium- and low-energy conditions were calculated to be 834 ± 16.5 MPa, 830 ± 7.1 MPa and 843 ± 7.1 MPa, respectively. The tensile

properties of the electron beam welds fall close to the tensile property data for cast Ti-6Al-4 V.

- Microstructural characterisation of the welds was performed using light microscopy and scanning electron microscopy, and a fine $\beta \rightarrow \alpha$ transformation product was observed within the weld fusion zone.
- Microhardness measurements were also performed on the three weld conditions and the hardness in the work-piece material was considerably lower (by approximately 50 points on the Vickers scale) than that measured in the weld fusion zone. This suggests that the mechanical properties of the patch welds are controlled by the microstructure and composition of the work-piece material rather than the electron beam welded joint.

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Author contribution(s)

Meurig Thomas: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing – original draft; Writing – review & editing.

Iain Todd: Conceptualization; Formal analysis; Investigation; Project administration; Supervision; Writing – review & editing.

Samuel Tammam-Williams: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Writing – review & editing.

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Declaration of conflicting interests

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