Study of Process Parameters on the Mechanical Properties of Electron Beam Welded Joints

V.Sandhya[1], M.Nagaphani Sastry[2], K.Hema Chandra Reddy[3]
[1]*Department of Mechanical Engineering, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad 500075, Telangana, India*
[2]*Department of Mechanical Engineering, G Pulla Reddy Engineering College, Kurnool 518007, Andhra Pradesh, India*
[3]*Department of Mechanical Engineering, JNT University, Anantapur 515001, Andhra Pradesh, India*

***Abstract*—This study investigates the influence of electron beam welding (EBW) process parameters on the mechanical properties of Ti6Al4V alloy joints through comprehensive experimental design and statistical analysis. Three critical welding parameters voltage (kV), current (mA), and speed (m/min) were systematically varied across three levels using Taguchi L9 orthogonal array design, and their effects on depth of penetration, bead width, hardness, ultimate tensile strength were evaluated. The results demonstrate that current is the most dominant factor across most responses, while voltage significantly influences and speed shows minimal to marginal effects on most properties.**

***Index Terms*—Electron Beam Welding, Voltage, Current, Speed**

I. INTRODUCTION

Titanium alloy Ti6Al4V, comprising approximately 6% Aluminum and 4% Vanadium, is one of the most widely used titanium alloys in aerospace, biomedical, and high-performance engineering applications due to its exceptional combination of high specific strength, excellent corrosion resistance, good biocompatibility, and favorable performance at elevated temperatures. The alloy exhibits a dual-phase microstructure consisting of hexagonal close-packed α-phase and body-centered cubic β-phase, which provides an optimal balance between strength and ductility that can be further tailored through thermomechanical processing and heat treatment. However, joining Ti6Al4V components presents significant challenges due to the material's high melting point, low thermal conductivity, high chemical reactivity at elevated temperatures, and susceptibility to hydrogen embrittlement and hot cracking. Electron beam welding (EBW) has emerged as a superior joining technique for titanium alloys, offering distinct advantages over conventional fusion welding processes including deep penetration capability, narrow heat-affected zones, minimal thermal distortion, high welding speeds, and the ability to operate in a high-vacuum environment that prevents atmospheric contamination and oxidation of the reactive titanium during welding. The high energy density and precise control of the electron beam enable the production of high-quality welds with excellent mechanical properties and minimal defects.

Despite the advantages of electron beam welding, the mechanical properties and microstructural characteristics of Ti6Al4V welded joints are highly sensitive to process parameters such as voltage, current, and speed, which collectively determine the heat input, cooling rates, and resulting weld pool dynamics. Improper parameter selection can lead to various defects including porosity, incomplete penetration, excessive grain coarsening in the fusion zone, cracking in the heat-affected zone due to residual stresses and phase transformations, and deterioration of mechanical properties such as strength and ductility. Previous studies have investigated individual aspects of EBW process optimization, but a comprehensive statistical analysis examining the relative contributions of multiple parameters to various mechanical and geometric weld characteristics remains essential for process control and quality assurance. This study employs Taguchi design of experiments methodology and analysis to systematically investigate the effects of three critical

EBW process parameters voltage, current, and speed on depth of penetration, bead width, hardness, ultimate tensile strength, yield strength, and percentage of elongation of Ti6Al4V welded joints. The research aims to identify the optimal parameter combination for performance and provide practical guidelines for achieving high-quality electron beam welded Ti6Al4V components with superior mechanical properties and structural integrity.

II. METHODOLOGY

The experimental investigation was conducted using Ti6Al4V alloy as the base material, with welding performed using an electron beam welding machine(Fig. 1) equipped with precise control systems for voltage, current, and speed. A Taguchi L9 orthogonal array design was employed to systematically study three process parameters at three levels each: voltage (A) at 45 kV, 50 kV, and 60 kV; current (B) at 5 mA, 15 mA, and 25 mA; and speed (C) at 800 mm/min, 1000 mm/min, and 1200 mm/min (Table 1). Nine experimental trials were conducted according to the orthogonal array (Table 2), with all welding operations performed under high vacuum conditions to prevent oxidation and contamination of the titanium alloy.

Fig.1 Electron Beam Welding Equipment

Table 1: Levels of process parameters

S. No.	Process Parameters	Level 1	Level 2	Level 3
1	Voltage A (kV)	45	50	60
2	Current B(mA)	5	15	25
3	Speed C (mm/min)	800	1000	1200

Following welding, specimens were prepared for metallographic examination, mechanical testing. Cross-sections of the welded joints were cut perpendicular to the welding direction, mounted, polished using standard metallographic procedures, and etched with Kroll's reagent (2% HF, 6% HNO_3, 92% H_2O) to reveal the microstructure. Depth of penetration and bead width were measured using optical microscopy.

Mechanical property evaluation included microhardness testing conducted across the weld cross-section using a Vickers hardness tester with appropriate load and dwell time, and tensile testing performed on standard specimens machined perpendicular to the weld seam according to ASTM E8 specifications to determine ultimate tensile strength, yield strength, and percentage of elongation. Analysis of Means (ANOM) was performed for each response characteristic to determine the statistical significance. The delta values, representing the difference between the maximum and minimum mean responses at different levels of each parameter, were calculated to rank the relative importance of the parameters.

III. RESULTS AND DISCUSSION

The EBW was performed according to Design of experiments using the process parameters and bead geometry, mechanical testing's such as tensile test and hardness tests were performed on the welded samples and the results are tabulated in Table 2.

Analysis Using the Column Effects Approach

Taguchi suggests a variety of approaches for analyzing findings, including the ranking method, column effect method, plotting method, ANOVA, and so on. The column effects approach is employed in this study to determine the interaction of the components.

The column effects approach involves studying the output values at different levels and determining the range. A greater range indicates a greater impact on the parameters. The column effects technique determines the range by examining the output values at different levels. Out of all the characteristics, the current has the greatest influence on yield strength when compared to all other process factors, followed by rotation speed shown in Table 5.

Table 2. Experimental Values after Test

	Process Parameters						
E.No.	A (kV)	B (mA)	C (mm/min)	Depth of penetration (mm)	Width (mm)	Hardness (HV)	UTS (MPa)
1	45	5	800	0.97	0.740	380	902
2	45	15	1000	1.304	0.912	418	926
3	45	25	1200	1.89	1.230	430	945
4	50	5	1000	1.09	0.791	390	918
5	50	15	1200	1.45	0.984	419	939
6	50	25	800	2.68	1.590	452	986
7	60	5	1200	1.33	0.923	402	934
8	60	15	800	2.31	1.470	438	952
9	60	25	1000	2.59	1.580	441	964

The Table 3 presents a column effects analysis for depth of penetration in electron beam welding of Ti6Al4V, showing the sum of responses at each level for the three process parameters: voltage (S1), current (S2), and speed (S3). The analysis reveals that current (S2) has the most substantial influence on penetration depth with a range of 3.77, demonstrating that current variation produces the largest change in weld penetration from Level 1 (3.39 mm) to Level 3 (7.16 mm), representing more than a doubling of penetration depth. voltage (S1) shows a moderate effect with a range of 2.066, where penetration increases progressively from Level 1 (4.164 mm) to Level 3 (6.23 mm), indicating that higher voltage consistently enhances beam energy and penetration capability. Speed (S3) exhibits the smallest influence with a range of only 1.29, where Level 1 produces the maximum penetration (5.96 mm) and Level 3 yields the minimum (4.67 mm), suggesting that slower speeds allow more time for heat input and deeper melting. The ranking of parameter importance based on range values is S2 (current) > S1 (voltage) > S3 (speed).

Table 3. Analysis using the column effects approach for Depth of penetration

S.No	S1(Sum of Depth of Penetration for Voltage)	S2 (Sum of Depth of Penetration for Current)	S3 (Sum of Depth of Penetration for Speed)
1	4.164	3.39	5.96
2	5.22	5.064	4.984
3	6.23	7.16	4.67
Range	2.066	3.77	1.29

The Table 4 presents a column effects analysis for weld bead width in electron beam welding of Ti6Al4V, showing the sum of responses at each level for the three process parameters: voltage (S1), current (S2), and speed (S3). The analysis demonstrates that current (S2) is overwhelmingly the most influential parameter with a range of 4.706, showing a dramatic increase in bead width from Level 1 (2.454 mm) to Level 3 (7.16 mm), nearly tripling the weld width and confirming that current directly controls the energy density and lateral heat spread in the weld pool. Voltage (S1) exhibits a moderate effect with a range of 1.091, where bead width increases progressively from Level 1 (2.882 mm) through Level 2 (3.365 mm) to Level 3 (3.973 mm), indicating that higher voltage enhances beam penetration power and creates wider fusion zones. speed (S3) shows minimal influence with the smallest range of 0.663, where Level 1 produces the widest bead (3.8 mm) and Level 3 yields the narrowest (3.137 mm), suggesting that faster travel speeds reduce the time available for lateral heat diffusion and result in narrower welds. The parameter ranking based on range values is S2 (current) >> S1 (voltage) > S3 (speed)

Table 4. Analysis using the column effects approach for Width

S.No	S1(Sum of width for Voltage)	S2 (Sum of width for Current)	S3 (Sum of width for Speed)
1	2.882	2.454	3.8
2	3.365	3.366	3.283
3	3.973	7.16	3.137
Range	1.091	4.706	0.663

Table 5. Analysis using the column effects approach for Hardness

S.No	S1(Sum of Hardness for Voltage)	S2 (Sum of Hardness for Current)	S3 (Sum of Hardness or Speed)
1	1228	1172	1270
2	1261	1275	1249
3	1281	1323	1251
Range	53	151	21

The table 5 presents a column effects analysis for hardness in electron beam welding of Ti6Al4V, showing the sum of hardness values at each level for the three process parameters: voltage (S1), current (S2), and speed (S3). The analysis reveals that current (S2) is the dominant factor affecting weld hardness with a range of 151, showing a progressive increase from Level 1 (1172 HV) through Level 2 (1275 HV) to Level 3 (1323 HV), indicating that higher current produces harder welds, likely due to increased cooling rates from deeper penetration and the formation of harder martensitic phases in the fusion zone and heat-affected zone. Voltage (S1) exhibits a moderate effect with a range of 53, where hardness increases steadily from Level 1 (1228 HV) to Level 3 (1281 HV), suggesting that higher voltage enhances the heat input and affects the phase transformation kinetics during cooling, resulting in harder microstructures. Speed (S3) shows minimal influence with the smallest range of only 21, where Level 1 produces the highest hardness (1270 HV) and Levels 2 and 3 show slightly lower values (1249 and 1251 HV respectively), indicating that slower speeds allow slightly longer cooling times that may affect the martensitic transformation and hardness distribution. The parameter importance ranking is S2 (current) >> S1 (voltage) >> S3 (speed).

Table 6. Analysis using the column effects approach for Tensile Strength

S.No	S1 (Sum of tensile strength for Voltage)	S2 (Sum of tensile strength for Current)	S3 (Sum of tensile strength for Speed)
1	2773	2754	2840
2	2843	2817	2808
3	2850	2895	2818
Range	77	141	32

This table presents a column effects analysis for ultimate tensile strength (UTS) in electron beam welding of Ti6Al4V, showing the sum of tensile strength values at each level for the three process parameters: voltage (S1), current (S2), and speed (S3). The analysis demonstrates that beam current (S2) is the most influential parameter with a range of 141 MPa, showing a progressive increase in tensile strength from Level 1 (2754 MPa) through Level 2 (2817 MPa) to Level 3 (2895 MPa), indicating that higher current produces stronger welds through better fusion, deeper penetration, and more complete joint formation that effectively transfers load across the weld. voltage (S1) exhibits a moderate effect with a range of 77 MPa, where tensile strength increases from Level 1 (2773 MPa) through Level 2 (2843 MPa) to Level 3 (2850 MPa), suggesting that higher voltage enhances weld quality by providing sufficient energy for complete melting and reducing defects like incomplete fusion or porosity that would compromise mechanical strength. Speed (S3) shows the smallest influence with a range of only 32 MPa, where Level 1 produces the highest strength (2840 MPa) while

Levels 2 and 3 show slightly lower values (2808 and 2818 MPa), indicating that slower welding speeds allow more thorough fusion and better metallurgical bonding, though the effect is relatively minor compared to current and voltage. The parameter ranking is S2 (current) >> S1 (voltage) > S3 (speed)

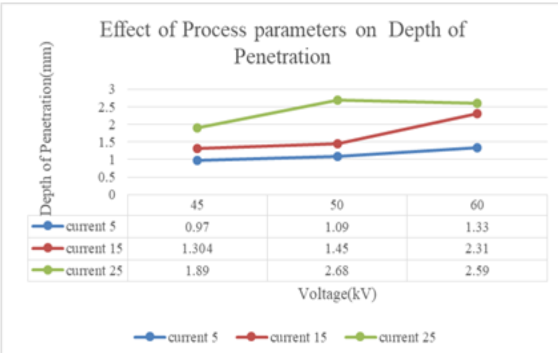

Fig 2. Effect of Process parameters on Depth of Penetration

The fig 2 illustrates how current and voltage jointly affect the depth of penetration in electron beam welding. Across all voltage levels, increasing the current produces a clear rise in penetration, with 25 mA consistently achieving the deepest welds, followed by 15 mA and then 5 mA. Penetration increases moderately with voltage for each current level, reflecting the added kinetic energy imparted to the electron beam; however, the separation between the three curves shows that current remains the dominant factor. The 25 mA condition peaks at 50 kV before slightly decreasing at 60 kV, suggesting a minor interaction effect, whereas the 15 mA and 5 mA curves exhibit steady upward trends. Overall, the graph indicates that higher current strongly enhances welding penetration, while voltage provides a secondary but consistent positive contribution.

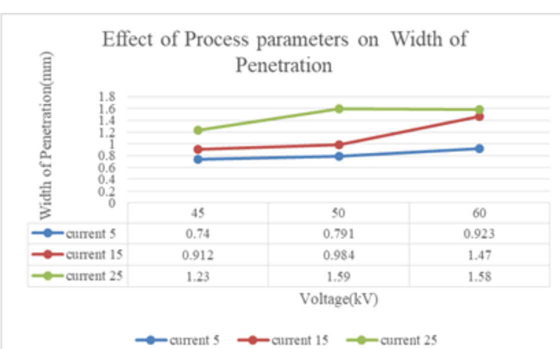

Fig 3. Effect of Process parameters on Width

The Fig 3 shows that both current and voltage influence the width of penetration in electron beam welding, with current having the stronger effect. At all voltage levels, the 25 mA condition produces the widest penetration, increasing from 1.23 mm at 45 kV to a peak of 1.59 mm at 50 kV, before slightly decreasing to 1.58 mm at 60 kV. The 15 mA curve shows a steady rise from 0.912 to 1.47 mm, indicating that width expands consistently with voltage at moderate currents. In contrast, the 5 mA condition yields the smallest widths, increasing only slightly from 0.74 to 0.923 mm. The generally upward trends confirm that higher voltage enhances beam spread, but the clear separation between the curves highlights that current predominantly governs weld width. Overall, the plot demonstrates that increased beam power, particularly through higher current, results in wider weld profiles.

Fig 4. shows that current is the dominant factor controlling hardness in electron-beam welded Ti-6Al-4V: the highest current (25 mA) consistently yields the hardest joints (~430 → 452 → 441 HV at 45, 50 and 60 kV), the mid current (15 mA) gives intermediate hardness (≈418–438 HV), and the lowest current (5 mA) the softest (≈383–402 HV). All three series rise modestly with increasing voltage, producing roughly parallel curves and creating distinct hardness bands separated by about 20–50 HV.A small peak at 50 kV for 25 mA suggests a minor optimal interaction, but the practical takeaway is that higher current (and higher voltage) increases hardness, likely via faster cooling and more α′ martensite, though this must be balanced against greater brittleness and reduced ductility.

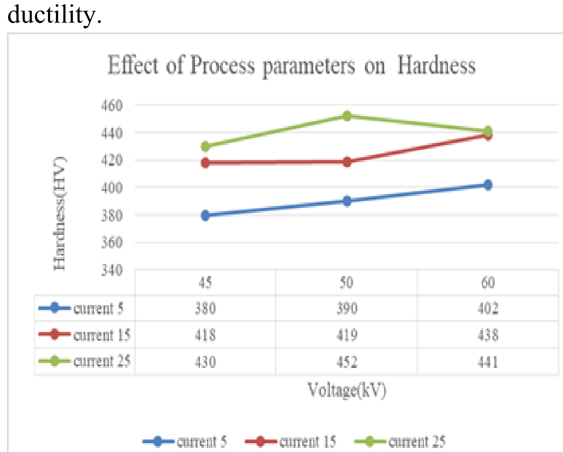

Fig 4. Effect of Process parameters on Hardness

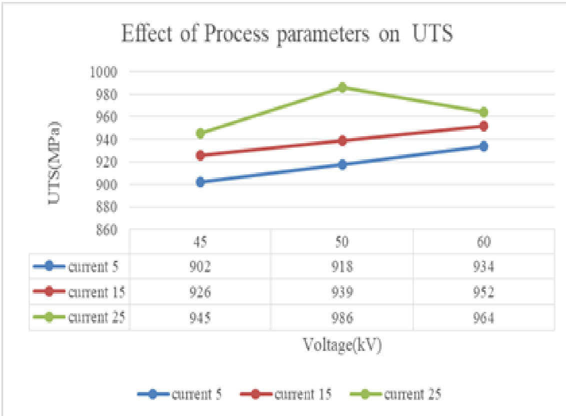

Fig 5. Effect of Process parameters on UTS

The figure shows that both voltage and current have a positive influence on the ultimate tensile strength (UTS) of electron-beam-welded joints, with current exerting the stronger effect. At every voltage level, the 25 mA condition produces the highest UTS, rising from 945 MPa at 45 kV to a peak of 986 MPa at 50 kV, followed by a slight decrease to 964 MPa at 60 kV. The 15 mA series follows a similar trend, steadily increasing from 926 to 952 MPa, while the 5 mA condition yields the lowest strengths, rising from 902 to 934 MPa. All three curves show modest upward trends with voltage, indicating that increased electron energy enhances weld consolidation, though the separation between curves confirms that current remains the dominant parameter. Overall, the plot demonstrates that higher beam power, particularly through increased current, improves joint tensile strength, with a minor interaction peak at 50 kV for the highest current level.

IV. CONCLUSIONS

1. Beam current is the dominant process parameter influencing all weld characteristics depth, width, hardness, and tensile strength showing consistently higher values at higher currents (25 mA > 15 mA > 5 mA).
2. Accelerating voltage provides a secondary but consistent positive effect, with most responses increasing moderately as voltage increases from 45 to 60 kV.
3. Depth of Penetration increases significantly with current, peaking around 50 kV for high current (25 mA), indicating an optimal interaction point between voltage and current.
4. Width of Penetration also increases with current, with 25 mA maintaining the widest welds; voltage contributes a smaller but steady widening effect.
5. Hardness rises strongly with increasing current, confirming that beam power controls cooling rate and microstructure formation; voltage offers a modest additional increase.
6. UTS improves with both parameters, but current again produces the largest effect, with peak UTS occurring at 50 kV for 25 mA before slightly declining at 60 kV.
7. Graphs consistently show parallel trends, indicating that voltage does not dramatically change behavior but elevates all responses uniformly.

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