Experimental Characterization of Electron Beam Welded SAE 5137H Thick Steel Plate

Prakash Kattire1,*, Valmik Bhawar1, Sandeep Thakare1, Sachin Patil1, Santosh Mane and Dr. Rajkumar Singh1
1Bharat Forge Ltd, Pune, Maharashtra, India
*prakash.kattire@bharatforge.com

Abstract. Electron beam welding is known for its narrow weld zone with high depth to width ratio, less heat affected zone, less distortion and contamination. Electron beam welding is fusion welding process, where high velocity electrons impinge on material joint to be welded and kinetic energy of this electron is transformed into heat upon impact to fuse the material. In the present work electron beam welding of 60 mm thick SAE 5137H steel is studied. Mechanical and metallurgical properties of electron beam welded joint of SAE 5137H were evaluated. Mechanical properties are analysed by tensile, impact and hardness test. Metallurgical properties are investigated through optical and scanning electron microscope. The hardness traverse across weld zone shows HV 370-380, about 18% increase in the tensile strength and very low toughness of weld joint compared to parent metal. Microstructural observation shows equiaxed dendrite in the fusion zone and partial grain refinement was found in the HAZ.

1. Introduction
In conventional welding high depth application of welding requires many passes and high preheating temperature generating more heat affected zone (HAZ) which affects joint mechanical strength. In case of electron beam welding permits deep penetration in single pass, generating narrow heat affected zone affecting less on the mechanical property [1]. Electron beam welding is fusion welding process for joining metals which uses highly focused beam of electrons as heat source. Very high velocity of electrons and high power density causes almost instantaneous local melting and vaporization of work-piece material. The electron beam is thus able to establish a ‘keyhole’ delivering heat, deep into material being welded. This produces narrow, parallel, fusion welding zone allowing butt welding in single pass for material thickness ranging from 0.025 mm to 300 mm [2-3]. Electron beam welding is initially employed in nuclear industry but rapidly spread into the aerospace, automobile and electronic industries. Nowadays it is employed over wide variety of application.

EBW is used for joining numerous metallic material including steel, aluminum, copper, titanium, nickel and magnesium and refractory metals. The process produces high integrity welds, with minimal thermal distortion and freedom from component oxidation.

SAE 5137H steel is used for auto component manufacturing. To improve manufacturability of intricate auto components they can be split and welded by electron beam welding. In automobile industry electron beam welding is used for welding of speed gear, torque convertor, shaft assemblies, differential gears, fuel injectors, planet carriers, turbocharger impellers etc.
Benjamin Joseph et al. (2012) [3] conducted study on 316L (N) austenitic stainless steel by varying welding parameter and mechanical and metallurgical properties were analysed. Mechanical properties of the weld metal are better than parent material. The variations in the mechanical properties were related with variation in the cooling rate of the weld metal. Walter D. [4] investigated electron beam welding structural steel heavy sections of high pressure valves and disc of turbine shafts. He addressed problem of porosity in electron beam welding of heavy sections by oscillatory deflection of focused electron beam spot and low welding speed. Takashi Inoue et al. (1993) [5] studied electron beam weldability of heavy steel plate. The study resulted into development of steel which can be electron beam welded to give good toughness. In the present study electron beam welding of SAE 5137H steel was done and mechanical and metallurgical testing were carried out to understand variation in the properties of the weld.

2. Experimentation

2.1. Experimental setup
The welded joint in butt configuration, was produced by an electron beam welding machine, Model 4500 of PTR Strahltechnik GmbH, located at Langenselbold, Germany (Figure 1). The machine has 150 kV generators and can produce very tall weld geometry. The work chamber pressure is maintained at 8 x 10^-4 mbar and beam generator maintained at 1 x 10^-5 mbar pressure. Different energy levels were obtained by varying accelerating voltage and beam current. Some trials were done to fix welding speed at which full penetration can be obtained in single pass.

2.2. Material Details
The SAE 5137H steel is used for the experimentation. The elemental composition of SAE 5137H is determined by spectroscopy and is shown in table 1. Two blocks of 100 x 100 mm with thickness of 60 mm is used for experimentation. The edges and surfaces of the blocks are machined such that zero gap is maintained between the surfaces while welding. Butt joint is used for welding. Blocks edges and surface were rinsed and polished with acetone before welding.

Figure 1. Experimental setup at PTR Germany.
2.3. Experimental details

2.3.1. Weld Block preprocessing. EB welding is carried out in vacuum and as result the process allows parts to be joined without any adverse oxidizing effects. It follows therefore, that the blocks should be free of any contaminants, such as cutting lubricant, anti-rusting oil etc. when they are assembled for welding. Hence, the pre-weld preparation stage is all important to the success of the operation. Following procedure is followed

- Parts are thoroughly degreased before assembly and joint faces are abraded and acetone washed
- To avoid deflection of electron beam by stray magnetism blocks are demagnetized

2.3.2. Preheating. Preheating involves heating the material to be welded either locally or in it’s entirety, to a specified temperature, before starting the welding operation. The main reason for preheating is to reduce the thermal gradient while welding and thus sudden quenching resulting in cold cracking [6]. The most critical factor in determining preheating temperature is carbon equivalent. As per structural welding code AWS D1.1 the empirical formula used to determine carbon equivalent is given below in equation 1.

\[
\% \text{CE} = \%C + \frac{(\text{Mn} + \text{Si})}{6} + \frac{(\text{Cr} + \text{Mo} + \text{V})}{5} + \frac{(\text{Ni} + \text{Cu})}{15}
\]  

(1)

SAE 5137H materials weldability is poor because of higher content of alloying element like carbon and manganese. With equation (1) carbon equivalent (CE) for SAE 5137H is 0.9%. The approximate recommended preheating temperature for CE above 0.6% is 205 to 375 °C. So keeping this in mind preheating is done in the electron beam welding machine vacuum chamber with the electron beam to 300-350°C with the predetermined optimized parameters as given in table 2. Usually steel that requires preheating must be kept at this temperature between weld passes, but characteristics of electron beam welding is that it can weld 60mm weld depth in single depth so preheating between passes is not required. Using same setup full penetration welding is done using the optimized parameters mentioned in table 2. Figure 2 shows the welded specimen. After welding the block was slowly cooled in furnace (post heating 250°C) to room temperature to reduce the risk of cracks. After welding sample was stress relieved for 570°C for 3hrs in separate furnace to reduce the residual stresses generated in welding.

2.4. Characterization.

Welded block was visually inspected and tested with die penetrant for surface defects. The block was also radiographed for internal soundness. Tensile samples were prepared with the weld oriented transverse to the gauge length as shown in the figure. 3 (ASTM E8). Tensile test samples were tested on MTS machine. For microstructural examination samples were prepared using standard metallographic method. 2% nital is used for etching the sample and microstructure of base material (BM), heat affected zone (HAZ) and fusion zone (FZ) were examined by optical microscope and Carl Zeiss make EVO18 scanning electron microscope (SEM). The Vickers micro hardness test was taken along the cross section of the welding across the weld with the load of 200g and time of 10s using
Clemex make micro hardness tester. Impact toughness studies using Charpy V-notch was done with the V-notch at the center of the weld.

**Table 1.** Chemical composition of SAE 5137H.

| Element (% Wt) | C  | Mn  | Si  | S   | P   | Cr  | Mo  | Ni  |
|----------------|----|-----|-----|-----|-----|-----|-----|-----|
| SAE5137        | 0.38 | 1.19 | 0.28 | 0.025 | 0.015 | 1.23 | 0.042 | 0.11 |

**Table 2.** Optimized electron beam welding parameter.

| Welding Plan | Accelerating voltage (kV) | Beam current (mA) | Welding speed (mm/s) | Focus current (mA) | Welding distance (mm) |
|--------------|---------------------------|-------------------|----------------------|-------------------|----------------------|
| Preheating   | 150                       | 18                | 40                   | 995               | 200                  |
| Welding      | 150                       | 65                | 10                   | 685               | 200                  |

**Figure 3.** Tensile sample used for testing EB welds.

3. **Result and discussion**

3.1 **Micro hardness**

The Transverse micro-hardness of cross section of weld zone was measured and plotted in figure 4. Figure 4 shows hardness variation in the fusion zone, HAZ and parent material. The hardness value of fusion zone is higher than HAZ and parent metal because of presence of fine dendritic microstructure.

**Figure 4.** Micro-hardness plot for across the weld zone.

3.2 **Microstructure**

Three different regions are found in the weld zone Microstructure, fusion zone, heat affected zone (HAZ) and base metal is shown in fig 5. Optical images of three zones are also shown in figure 6. Fusion zone shows equiaxed dendritic structure with ferrite and martensitic structure. HAZ can be divided into two regions. 1st region near fusion zone which cools slower because of adjacent hot fusion zone forms coarse grain HAZ and 2nd region is near base metal where fine grain HAZ is
formed because of faster cooling rate due cool adjacent base metal [7]. HAZ zone shows presence of ferrite and fine perlite lamellae and parent material showing soft ferrite and perlite microstructure.

Figure5. Electron beam welding microstructure.

Figure6. Optical images of a) Fusion Zone b) HAZ zone c) Base Material.

3.3 Transverse Tensile strength
Transverse tensile strength results are shown in table 3. In all three samples tensile test failure location is in base metal (as shown in fig. 7) so we can say that weld material is stronger than parent metal. 18% increase in the tensile strength of material was found after electron beam welding. Better properties can be explained by microstructure results showing fine dendritic microstructure in the weld zone which is result of higher cooling rate in welding

Table 3. Transverse tensile test result

| Specimen No. | 1    | 2    | 3    |
|--------------|------|------|------|
| Ultimate tensile strength (MPa) | 871  | 875  | 904  |
| Base Metal strength (MPa) | 747  |      |      |

Figure7. Tensile test failure location in a) EBW b) Parent Material.
3.4 Impact Strength

Impact strength of welded and parent material is shown in table 4. Toughness of the weld joint reduced significantly. Since EBW uses no filler material so the composition of weld metal is same as base metal and weld metal is cast structure which formed with high cooling rate. So there is loss in toughness of material in as welded condition [8].

| Specimen No. | 1    | 2    | 3    |
|--------------|------|------|------|
| Impact strength (J) | 11.2 | 12.5 | 11.8 |
| Base Metal Impact strength (J) | 48   |      |      |

4. Conclusion

Electron beam welding can be used in high depth application in automotive industry. Electron beam welding study carried out on SAE 5137H steel shows following weld characteristics.

- Average 360-378 HV hardness is found in the fusion zone is higher than parent material this is due to fusion zone has fine dendritic microstructure.
- Electron beam welding has higher tensile strength than parent metal, because of less heat input and low HAZ.
- As compared to parent material weld is very low toughness as weld metal is like a cast structure and formed by high cooling rate.

References

[1] Gokul Ananth M., B.Sathish Babu, P.Chakravarthy, K.Jayakumar, A.Manickavasagam, N.V.S Arunprakash, K.M. Gopalanrishnan, “Experimental Investigations on Electron Beam Welding of Austenitic/Ferritic Stainless Steel for Space Applications”, IJRMET Vol. 3, Issue 2, May - Oct 2013

[2] Weglowski M. st., S. Blacha, A. Phillips, “Electron beam welding- techniques and trends- Review”, Vacuum 130 (2016), 72-92

[3] Benjamin Joseph, D. Katherasan P. Sathiya and C. V. Srinivas Murthy, “Weld metal characterization of 316L(N) austenitic stainless steel by electron beam welding process”, International Journal of Engineering, Science and Technology, Vol. 4, No. 2, 2012, pp. 169-176

[4] Dietrich W., “Investigation Into Electron Beam Welding of Heavy Sections”, AWS 59th Annual Meeting held in New Orleans, Louisiana,during April 3-7, 1978

[5] Takashi I., Masahiro O., Yukio T., Yukio T., Koji T., Kunio K., Rikio C., Seiji I., “Development of heavy steel plates with excellent electron beam weldability ”, Nippon steel technical report No. 58, July 1993

[6] Srivastava B. K., Dr. Tewari S. P., Jyoti P., “ Review on effect of preheating and or post weld heat treatment on mechanical behaviour of ferrous metal”, International Journal of Engineering Science and Technology Vol. 2(4), 2010, 625-631

[7] Blacha S., M.St. Węglowski, S. Dymek, M. Kopański, “Microstructural Characterization and Mechanical Properties of Electron Beam Welded Joint of High Strength Steel Grade S690QL”, Arch. Metall. Mater., Vol. 61 (2016), No 2B, p. 1193–1200

[8] Sivaramakrishnan N., K. S. Raja and K. Prasad Rao, “Effect of Post-weld Heat Treatment on Weld Metal Impact Toughness of a Semi-Austenitic PH Stainless Steel”, Welding Research Supplement, 200-s-207-s, auguast 1994