ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 6, November 2015

Prediction of Heat Affected Zone and Effect of Heat Input in GTA Welded Al Alloy 6061

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***Abstract*— Aluminum Alloy 6061 is an Al-Mg-Si alloy employed in aircraft, automobiles, road containers and high speed trains due to their low density, high specific strength and excellent corrosion resistance. In this paper, the effects of heat input on Gas Tungsten Arc (GTA) welded Aluminium Alloy 6061 have been studied at various combinations of pulse parameters with sinusoidal AC wave. Also the effect of heat input on the microstructure, heat affected zone (HAZ) width, grain size and other mechanical properties of the weld joint has been studied.**

***Index Terms*— AA6061, GTAW, Heat Input, Microstructure of welded joints.**

I. INTRODUCTION

Aluminium alloy 6061 (Al–Mg–Si alloy) is widely used in the fabrication of food processing equipment, chemical containers, passenger cars, road tankers and railway transport systems due to its high strength, excellent weldability and resistance to corrosion. As these Al alloys (6xxx series) are precipitation-hardened, they suffer from a strength reduction in heat affected zone (HAZ) and like most face-centered cubic metals, they do not exhibit clear endurance limit [1].

Welding of aluminium is generally performed either by gas metal arc welding (GMAW) or gas tungsten arc welding (GTAW). Lots of difficulties are associated with this kind of joining process, mainly related to the presence of a oxide layer, high thermal conductivity, high coefficient of thermal expansion, solidification shrinkage and, above all, high solubility of hydrogen in the molten state. Further problems occur when attention is focused on heat-treatable alloys, since heat, provided by the welding process, is responsible for the decay of mechanical properties, due to phase transformations and softening.

GTAW is an arc welding process, where arc is produced between non-consumable tungsten electrode and base metal. Pulsed GTA welding process is frequently used for welding of aluminium alloys as heat input during welding can be precisely controlled. This process is strongly characterized by bead geometry, which plays an important role in determining mechanical properties of the weld [2]. Pulse process variables are controlling factor for heat input, which in turn leads to grain refinement in fusion zone, width reduction of HAZ, segregation of alloying elements, reducing hot cracking sensitivity and residual stresses [3, 4].

Improved mechanical properties of weld are achieved by using current pulsing due to the grain refinement occurring in the fusion zone. The main aim of pulsing is to achieve maximum penetration without excessive heat built-up. The use of high current pulses is to penetrate deep and cater for longer arc period at lower current. Deep penetration in pulsed current welding is produced by arc pressure at peak for longer durations [4]. In addition to this argon – helium gas mixture offers certain advantages by increasing heat input of the arc during welding. Argon is known for stable arc with better arc ignition whereas helium provides higher thermal conductivity. There exists a linear relationship between heat input of a weld and maximum temperature at a given distance from the weld centre line. It shows that pulsed arc welds are cooler and exhibit less thermal distortion than conventional GTA welds of the same penetration [5]. Heat input is typically calculated as follows: $H = [60EI]/1000S$, Where H = Heat Input (kJ/mm), E = Arc Voltage (Volts), I = Current (Amps) and S = Travel Speed (mm/min).

The evolution of microstructure in weld fusion zone is influenced by current pulsing and cyclic variations of energy input into the weld pool causing thermal fluctuations. Consequently this leads to periodic interruption in solidification process. As pulse current decays, solid–liquid interface advances towards the arc and becomes susceptible for disturbances in the arc formation. As current increases again in the subsequent pulse, the growth of dendrites can also occur. Current pulsing also results in periodic variations of the arc forces resulting in additional fluid flow, which lowers the temperature in front of the solidifying interface. Furthermore, the temperature fluctuations inherent in pulsed welding leads to a continual change in the weld pool size and shape favoring growth of new grains. It is to be understood that effective heat input for unit volume of weld pool should be considerably less in pulse current welds and thus expecting the average weld pool temperatures to be low [6].

A weldment basically consists of five micro structurally distinct regions normally identified as fusion zone, unmixed region, partially melted region, HAZ and unaffected base metal. The HAZ is the portion of weld joint which experiences peak temperatures high enough to produce solid-state micro structural changes but they are too low to cause any melting. Every point of the weldment in the HAZ relative to the fusion line is subjected to unique thermal experience during welding, in terms of both maximum temperature and cooling rate. Thus, each point has its own micro structural features and corrosion susceptibility. Partially melted region extends usually one or two grains into the HAZ relative to the fusion line. It is characterized by grain boundary liquation, which may result in liquation cracking. An increase in the pulse frequency refines grain structure of weld metal using pulses of short duration. At a given frequency, long pulse duration produces coarser grain structure than shorter pulse duration. Further increase in the peak current leads to coarseness of grain structure [7].

II. EXPERIMENTAL PROCEDURE

In this study, five Al alloy 6061 GTA welded 5.0 mm thick samples were undertaken. These samples were welded with AA5356 filler rods. The chemical compositions of the base metals and filler rod are shown in Table 1. Samples were machined to the required dimensions (300 x 150 x 5 mm) and edges were prepared for butt welding. Welding of the samples was carried out using an automatic Pulse TIG welding machine (TRITON 220V AC/DC). Samples were welded at the parameters shown in Table 2. Specimens were separated out from the transverse section of the weld joint and polished using a standard metallographic procedure, which consisted of molding, polishing and etching. Specimens were etched with Keller’s reagent. The following welding conditions were maintained constant during the welding:

a) Electrode : Tungsten with 2% Zirconium
b) Electrode size : 2.4 mm diameter
c) Shielding gas : 30% helium + 70% argon
d) Shielding gas flow rate : 8 Litre /min
e) Filler diameter : 3.15 mm
f) Welding speed : 4.16 mm/sec
g) Electric voltage : 16.8 V
h) AC Balance % : 0 (sinusoidal)

Table 1: Chemical Composition of Base and Filler Metal (Weight %)

Alloy	Al	Mg	Si	Others
6061	96.8	1.10	0.70	Rest
5356	95.2	4.8	-	

Table 2: Pulse GTA Welding Parameters

Process Parameters	Unit	Sample				
		1	2	3	4	5
Pulse Current	A	150	150	180	195	210
Base Current	A	105	135	75	105	90
Pulse Frequency	Hz	100	150	100	50	50
Pulse Duty Cycle	%	60	90	90	75	90

III. TESTING AND ANALYSIS

The microstructures of the specimens were studied under optical microscope (GX51 N-233U, Olympus). Image analysis of micrographs of the weld metal was carried out using image analyzing software .The calculation of heat input for the pulse current welding process can be done by mean current using the relationship. $Im = [I_p t_p + I_b t_b]/t_T$ on heat input equation, where Im is mean current, I_p is pulse current, t_p is time on peak current, I_b is base current, t_b is time on base current, t_T is total time. The heat input for various samples are tabulated in the Table 3.

Table 3: Heat Input, HAZ width and ASTM Grain Size Number of Samples

Sample No	Tp sec	Tb sec	I mean (A)	Heat Input (J/mm)	HAZ Width (µm)	ASTM Grain Size No (Weld Zone)
1	0.006	0.0040	132.0	31.9	1124.80	10.72
2	0.006	0.0007	148.4	35.9	1246.12	10.18
3	0.009	0.0010	169.5`	41.0	1299.04	10.04
4	0.015	0.0050	172.5	41.8	1355.18	09.12
5	0.018	0.0020	198.0	48.0	1598.61	08.48

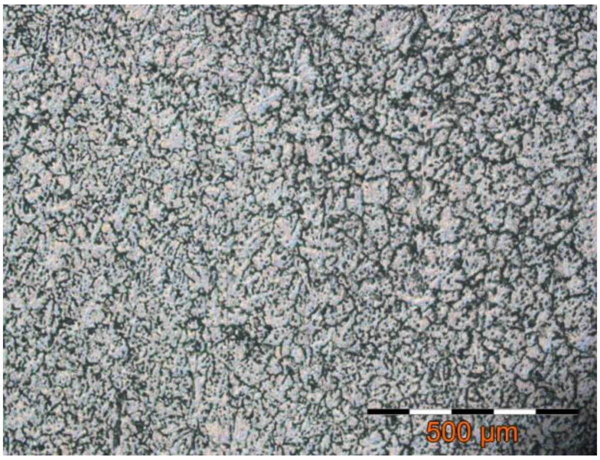

Fig 1(a): Microstructure of Weld Zone

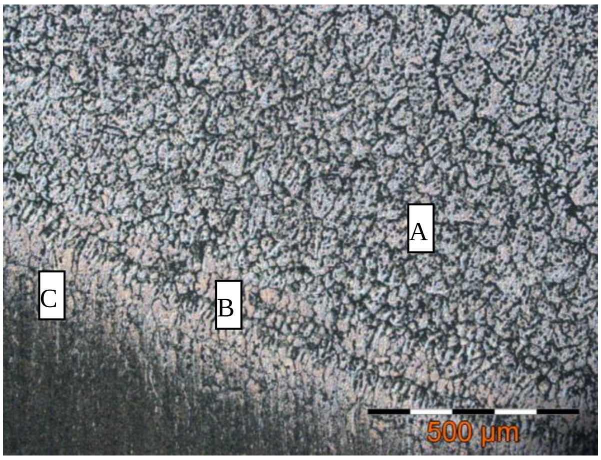

Fig 1 (b): Microstructure of Welded AA6061 (A–Weld Zone, B–Fusion Boundary and C–HAZ)

1) Micro structural Study: The microstructure of welded AA6061 is shown in Fig 1, in which weld zone (WZ), fusion boundary (FB) and HAZ are clearly visible. The grains in weld zone are coarser due to as cast nature of the weld and fine equiaxed grains are present at the fusion boundary. HAZ has large columnar grains (columnar grains generally occur in directional solidification or cold worked elongated grains in metal) near fusion boundary and the size reduces towards the unaffected base metal. With the help of image analyzer system, HAZ width and ASTM grain size number were calculated from microstructures of samples. The microstructural quantity known as the ASTM micro grain size number (n), is defined by the following relationship: $N = 2^{n-1}$, where N is the number of grain per square inch at 100x.

The effect of heat input on HAZ width and ASTM grain size number are shown in Fig 2 and 3. The data available from Table 3, Fig 2 and 3 clearly shows as heat input increases the HAZ width and ASTM grain size also increases. Fig 4 and 5 shows the variation of grain size from weld centre to unaffected base metal for samples 1 to 5. Here ASTM grain number is smallest in weld zone and increases at fusion boundary since it is having finer grains.

2) Microhardness Study: Microhardness (Vickers) was measured from the one fusion boundary to another fusion boundary with a load of 200 gf as shown in Fig 5. Microhardness testing is an indentation method for measuring the hardness of a material on a microscopic scale. A precision diamond indenter is impressed into the material at load. The impression length, measured microscopically and the test load are used to calculate a hardness value. The variations of micro hardness from the weld centre were given in Fig 6.

IV. DISCUSSION

Microstructures: Welds in heat treatable alloys generally exhibit four micro structural zones (weld zone, fusion boundary, HAZ and unaffected base metal as explained in Fig 1 [8]. The weld zone is a mixture consisting of melted base plate and 5356 filler metal with an as-cast dendritic structure. The grain size in the cast metal did not vary significantly in the various weldments. The fusion zone, an area in which inter-granular melting occurred, a butted the weld metal and contained portions of the original parent structure with partially melted and re-solidified eutectic at the grain boundaries resulting from temperatures between the liquidus and solidus. The HAZ is the area where temperatures were below the solidus of the alloy but high enough to dissolve the precipitates that were originally present in the parent plate. Temperatures in this area during welding were 600^0F or higher, resulting in partial or complete solution heat treatment. The microstructure varied from fine precipitates, associated principally with the grain boundaries, to coarse precipitates dispersed throughout the grain matrix.

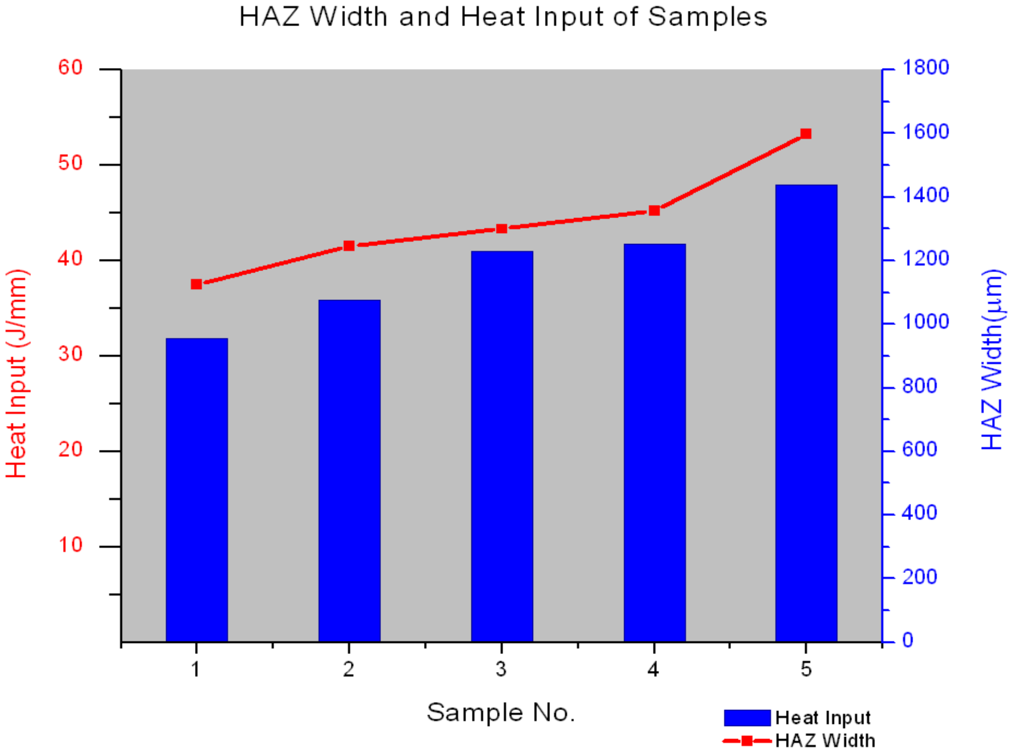

Fig 2: Variation of HAZ Width and Heat Input of Samples

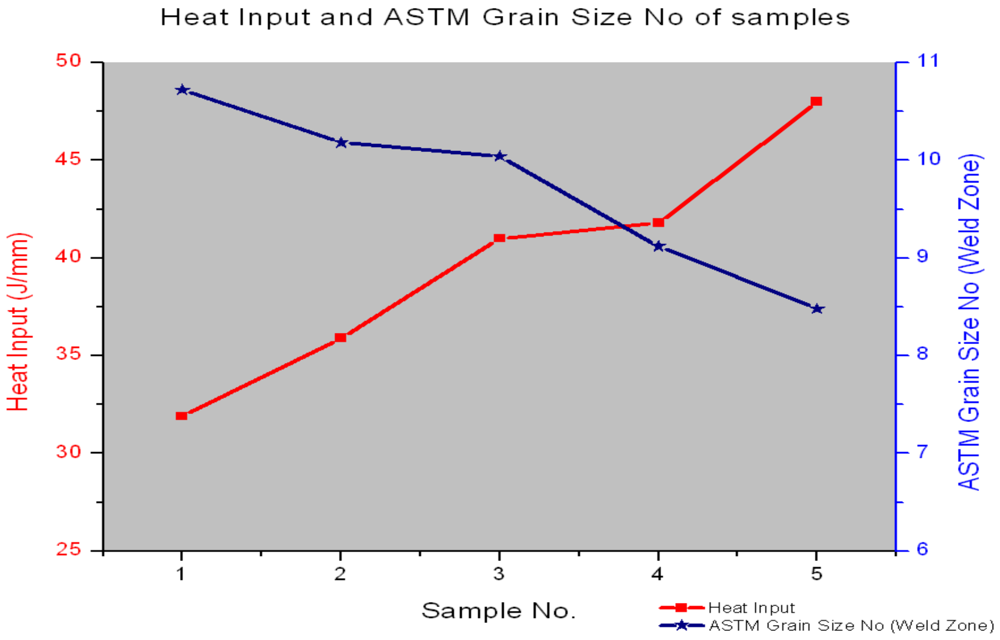

Fig 3: Variation of Heat Input and ASTM Grain Size Number of samples

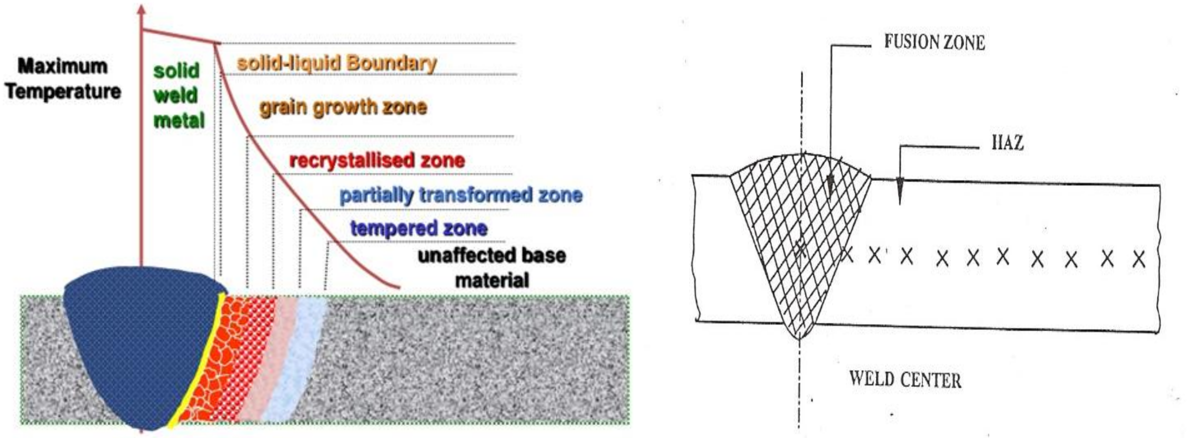

Fig 4: (a) Geometry of Weld, (b) Schematic Diagram for Measurement of Grain Size and Microhardness

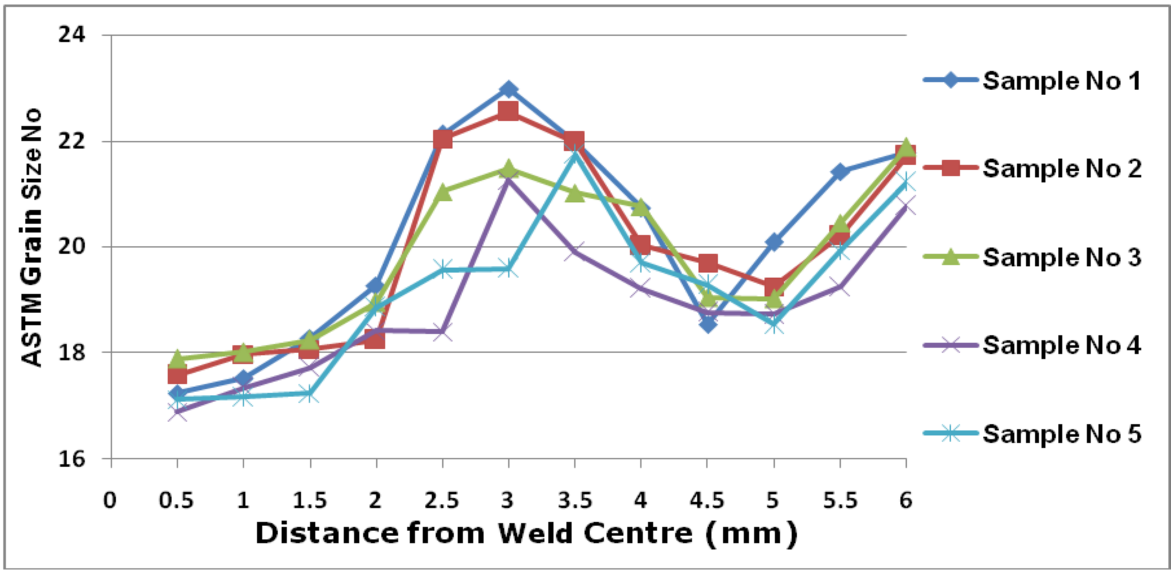

Fig 5: Grain Size Number of Samples from the Weld Centre

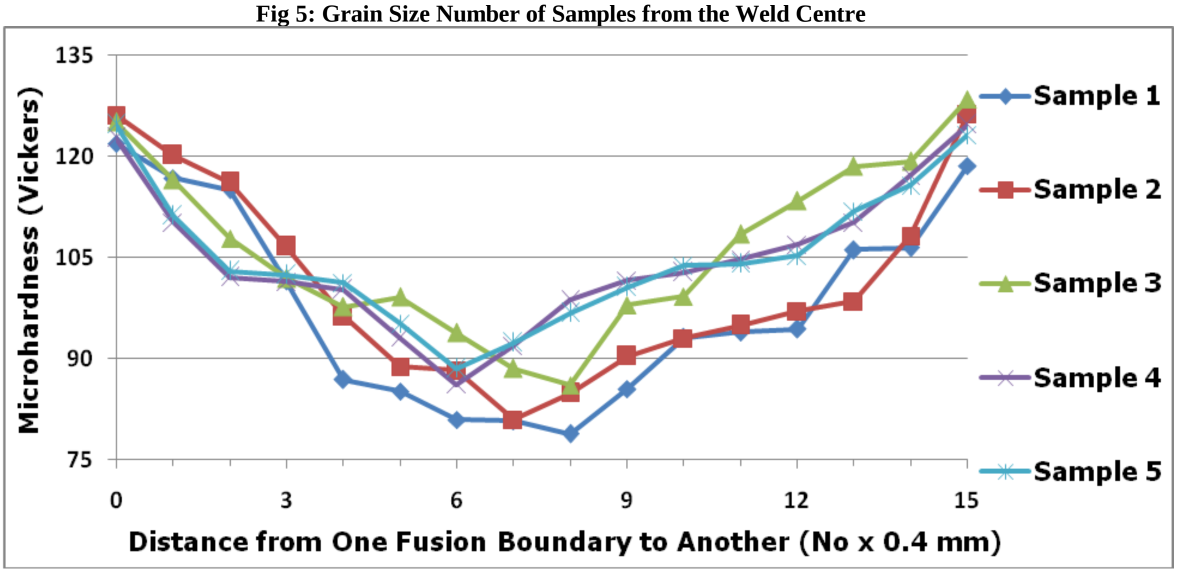

Fig 6: Microhardness of Samples from One Fusion Boundary to Another

Grain size: From Fig 5 and Table 3, weld zone of all samples are occupied by coarse due to as-cast nature of microstructure, which has low hardness (almost 40% less than the parent metal) and lack strengthening phases. The grain in the centre of weld is of largest size due to the slow cooling rate at centre and this size reduces towards the fusion boundary. As heat input increases, the width of weld zone becomes wider and generates coarse grains, which is very much unfavorable for both mechanical properties of weld joint as well as strength.

Heat Input: The rate of heat input per inch of weld in arc welding is proportional to the welding voltage and current and inversely proportional to the welding speed. Most of the heat of welding will be dissipated by conduction through the adjacent metal, although a small amount will be lost by radiation and convection to the surrounding environment. From Table 4 it is sure that higher heat input generates wider HAZ due to high thermal conductivity of the base metal. In heat treatable aluminium alloys, microstructure distribution of HAZ exhibits a complicated distribution due to temperature variations. Parent material properties appear to be unaffected in locations where temperature during welding does not exceed 400^0F. Metal heated in the $400\text{-}600^0$ F temperature range undergoes hardness reductions which are not restored by natural or artificial post-weld aging. This is HAZ softening zone. The width of the soft zone depends on the peak temperature heating / cooling rate, dissolution and / or growth of precipitates and formation of stable phases. Loss of hardness and strength in HAZ is due to the dissolution and coarsening of Mg^2Si phase, the main strengthening phase in Al-Mg-Si alloys. Wider HAZ is also unfavorable for the mechanical properties of the weld joint, due to presence of coarse grains. Metal heated to above 600^0F shows the greatest reduction in hardness immediately after welding, but it cab be gradually recovered by increasing its hardness according to the time elapsed after welding due to excellent natural age hardening.

Microhardness: There is a general correlation between hardness and tensile strength for aluminum alloys having similar chemical composition. Therefore, microhardness in the HAZ provided a convenient and simple means of studying the effect of heat input during welding on strength. There were mainly three regions in which microhardness shows significant change, the weld zone; fusion boundary and HAZ. From Fig 6, we can see that weld zone is having very low microhardness for all samples. As it moves from the weld centre microhardness increases at fusion boundary due to fine grains as it gets lesser time for solidification and then decreases at HAZ due to coarser elongated grains. Microhardness varies at a range of 70 VHN to 130 VHN from weld centre to parent metal. Also it was observed that the fall in microhardness moves away from weld centre from sample 1 to 5. This shows clearly the effect of heat input on microhardness.

V. CONCLUSION

From the above results we can conclude that:

a) Mechanical properties of the weld zone depend on the grain size. The unfavorable mechanical properties of the weld joints are due to coarse grains.

b) High heat input generates wider weld zone and HAZ, which reduces the joint strength and weld hardness.

c) Metal heated in the $400\text{-}600^0$F temperature range undergoes hardness reductions which are not restored by natural or artificial post-weld aging. Therefore minimum heat input, which can be controlled by optimum process parameters, should be used in welding of aluminium alloys.

ACKNOWLEDGMENT

The author wishes to thank Vehicles Research & Development Establishment (VRDE), Ahmednagar for providing all the facilities for carrying out the experiments, and the scientists / staff of VRDE for their support and assistance.

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