Gas metal arc welding process parameter optimization for AA7075 T6

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Abstract. Aluminium alloy 7075 T6 weld joints having size of plates 125 mm ×100 mm × 10 mm experimented to investigate the effects of process input parameters on the thermal, mechanical properties of GMAW. The process input parameters like current (A), heat flux (Q), flow rate of gas (G), speed of welding (S), wire feed rate (F) & shielding gas are affecting the thermal, metallurgical & mechanical properties of weldment. This experimental study aims at developing mathematical models for bead height (HB), bead width (WB) and bead penetration (PB) and investigating the effects of four process parameters. This experimental analysis aims at temperature study for selection of process parameter & prediction of the bead geometry. The heat flows during welding process controls the grain size & material properties. The temperature spread is vital in affecting characteristic of weld joint. Transient thermal analysis gives temperature & residual stress distribution at varied mode of heat transfer phases.

Keywords: Aluminium Alloy 7075 T6, Gas Metal Arc Welding (GMAW), Transient thermal analysis, microstructure.

1. Introduction & Literature Review

Two different components are connected together by melting & then further solidification of nearby portion in fusion welding process. The size of fusion and affects on the weldment properties is controls by flow of heat in welding process. The distribution of the temperature, composition of chemicals & geometry of weld bead of the weld joints affects on the thermal, metallurgical and mechanical properties of weldment. Now a day the automotive industries have been using light material like aluminium than that of conventional material like steel. The aluminum alloy weld joint is influence by the following physical properties.
- Temperature range of solidification.
- Thermal conductivity
- Thermal expansion coefficients
- Oxide formation at surface

The advantages of using GMAW for joining of aluminium alloy 7075 T6 is of high efficiency, better quality of weld, less manufacturing cost, automation in manufacturing, less production time than that of traditional joining processes. Nowadays GMAW process is used very widely in various applications like Structure assembly, automotive industries, piping industry, in construction machineries, ships etc. Almost all commercial metals like aluminium, carbon steel, nickel, titanium alloy, carbon steel, low and high alloy steel are joined by GMAW process. To achieve high quality weld the proper selection of welding parameter, proper handling of welding equipment, welding knowledge and welding technology plays a very important role, otherwise it leads to defects in the welding.

In the past, Aluminium alloy 7075 has been the standard workhorse 7XXX series alloy within the...
Aerospace industry, transportable bridge girders, military vehicles, road tankers and railway transport systems. It was the first successful Al-Zn-Mg-Cu high strength alloy using the beneficial effects of the alloying addition of chromium to develop good stress-corrosion cracking resistance in sheet products. Although other 7XXX alloys have since been developed with improved specific properties, alloy 7075 remains the baseline with a good balance of properties required for aerospace applications.

The GMAW is of two types: continuous current & pulsed current GMAW. The continuous current methods lead to sensitivity to porosity and fusion defects, so in order to overcome this limitation of continuous current GMAW process a new method is developed. The pulse current GMAW forms single drop of molten metal per pulse at the tip of electrode. In pulse current method there is no continuous supply of current, the current drops only when there is no need of extra power, it leads to generation of cooling off period. Because of this generation of cooling off period pulse current GMAW is used on thin materials to control thermal distortion.

The weldment quality is dependent on geometry of weld bead which is influenced by the input process parameter. So selection of proper welding parameter is one of the biggest works in the GMAW process. The prediction and measure of size of weld bead is very difficult where it is influence by speed of welding and power usages. One of the methods for prediction and measuring size of weld bead is experimentation. But there are some uncertainties in the data obtained during experimentation; also heat data could not be generated in these trials. The prediction of weld joint size can be done by use of mathematical model, but the main disadvantage in this is variation in thermal properties with temperature not taken into the consideration. So in thermal analysis the GMAW process is to be investigating through FEA. A 3 dimensional FEA model need to develop to do the simulation of GMAW process. The effect of heat input on the GMAW is to be studied in this paper. To check finite element model, the degree of experiments of GMAW process of thin piece of AA 7075 T6 is to be carried to investigate welding bead profile.

Kambale A.G. et al investigated the GMAW process parameters & their effects and also done transient thermal analysis of AISI321 steel. In this AISI321 steel plate piece of size 150 mm × 120 mm × 10 mm made with a 300 groove on 120 mm side on both work piece plate. The sample is prepared as per the ASTM. Two plates are welded together by means of GMAW process under different input process parameter like current, voltage, gas flow rate, welding speed etc. Total 28 experiments are conducted under different input process parameter. Its thermal, metallurgical and mechanical behavior is checked. Welded zone exhibits maximum temperature and gradual movement across welded plates during conduction. However, central part is affected with convection. Uniform grain distribution is seen in the base metal microstructure. Parallel to rolling direction, annealing twins and deformation bands are found. Heat affected zone has coarse grain structure and cast structure with changing effects are found on either sides.

Kambale A.G. et al investigated GMAW process parameter and its effects on geometry of weld bead, tension strength, hardness, change in microstructure and thermal-mechanical analysis of AISI202 steel. The steel plate piece of AISI202 having size 125 mm × 100 mm × 10 mm is prepared by making a groove of 300 to each work piece on 100 mm side of plate. Two plates are welded together by means of GMAW process under different input process parameter like current, voltage, gas flow rate, welding speed etc. Total 28 experiments are conducted under different input process parameter. Total 28 experiments are conducted under different input process parameter. Its thermal, metallurgical and mechanical behavior is checked. From this it is observed that the occurrence of coarse grain and dendritic structure in welded zone gives less tension strength as well as fracture of weldment in welded zone. The stresses are more in weld zone and HAZ. The decrease in temperature from welded zone up to the base metal zone results in decrease stresses in welded joint piece.

M.I.S Ismail, et al studied temperature analysis on a welded joint of aluminum alloy 6061 in GMAW. In this AA6061 plates with thickness 3mm is cut into two pieces of 100 mm × 125 mm. The sheets are welded together by GMAW process under controlled input process parameter like speed of welding; arc voltage, and current, feed rate of wire and flow rate of gas keep constant in the experimentation. From this it is found that the distribution of temperature is depend on arc voltage and
welding speed. The input heat to weld area is transfer at faster rate initially in the thickness direction of plate and further in the width of plate.

B P Abhishek et al has done experimentation and FEA of for SS 303 grade by use of GMAW process to find thermally induced residual stresses. The flow of the temperatures in welding joint of AISI303 grade high strength steel is found by FEM and experimentation has done to validate the developed thermal-mechanical finite element model using the gas metal arc welding process. In this AISI202 steel plate piece having size of 125 mm × 100 mm× 10 mm is prepared & also 30º grooves is made on each work piece on side of 100 mm. Two plates are welded together by means of GMAW process. It is found that maximum temperature occurs at the welded zone. Temperature is decreasing when goes away from the centre of the weldment. Near weld zone maximum residual compressive stress are observed and near the end surfaces in the base material maximum tension stress are observed.

It is observed from the literature that the scientists and authors have studied on different work piece materials having different thickness from 5mm to 8 mm thickness rolled plates for single V groove butt weld joint by using various welding types such as continuous current SMAW, pulsed current SMAW, MIG, and TIG. By using various methods for study has reported that it is necessary to study and investigate 10 mm to 12 mm AA 7075 T6 thick plate weld joint.

2. Methodology

2.1 GMAW Machine

The experimentation is conducted on a 3 phase, 50 Hz, 300 Ampere, fan air cooling GMAW machine pioneered by Lorch company, Germany. The work piece is fixed to the structure and held on its position by using clamp to avoid distortion. Welding torch follows appropriate path, while all other parameters are controlled by GMAW machine. The current changes automatically by varying the voltage. So, current is excluded as process parameter. Hence, voltage, feed rate of wire, flow rate of gas and speed of welding are considered as a process parameter for the experimentation. Figure shows the GMAW experimentation setup.

![Figure 1. Experimental welding setup](image)

2.2 AA7075T6 Material and Readiness of Sample

Aluminium alloy 7075 consists of Zn as the major alloying element. It is having strength is nearly to steel. AA 7075 having very good fatigue strength and considerable machinability, but resistance to
corrosion is less in comparison with other aluminium alloy. The use of Aluminium alloy 7075 is less due to its high cost. It is generally used in the application where less costly alloy is not suitable.

Table 1. Composition of AA7075 T6

| Sr.No. | Name | Composition in % |
|-------|------|------------------|
| 1     | Zn   | 5.510            |
| 2     | Pb   | 0.036            |
| 3     | Sn   | 0.028            |
| 4     | S    | 0.008            |
| 5     | P    | 0.022            |
| 6     | Cr   | 0.210            |
| 7     | Mn   | 0.190            |
| 8     | Si   | 0.220            |
| 9     | Mg   | 2.760            |
| 10    | Fe   | 0.270            |
| 11    | Ti   | 0.090            |
| 12    | Cu   | 1.470            |
| 13    | Ni   | 0.040            |
| 14    | Al   | 89.146           |

The AA 7075 T6 plate pieces of size 125 mm × 100 mm× 10 mm size is made. The 30° groove is made on both plates on the 100 mm side as per the design. A gap of 2 mm kept between two plates. Fig.2 shows the pair of specimen ready for the GMAW.

2.3 Process parameter, their selection as per design of matrix

To achieve better weld bead geometry, process parameters play a very important role. So, selection of proper parameters is needed. The input parameters selected for the process are heat flux, current, speed of welding, feed rate of wire, flow rate of gas, and the output parameters are thermal behavior of material and weld bead geometry. The size of weld bead affects on the mechanical properties of the welded work piece, so tensile strength is considered as an output parameter in this process. The 4 input process parameters are chosen at 5 different levels. These 4 input process parameters are selected depending on their effects on weld joint size and aesthetic look of the weld joint. Acceptable number of parameters should be at least 5. The variation among all 4 input parameter is chosen by conducting a mix of experiments for a quality welds joint eliminating surface defects. If the input parameters working range is less or more than the predefined range, then
A desirable weld joint will not achieve. The maximum limits of input process parameters are numbered as +2 and the minimum limits are numbered as -2. The coded values for in between ranges are found out by formula as below:

\[ x_i = \frac{2(x - (x_{\text{max}} + x_{\text{min}}))}{(x_{\text{max}} - x_{\text{min}})} \]

Where \( x_i \) the required numbered value of a input process parameter \( x \), \( x \) any value of the input parameter in between \( X_{\text{max}} \) to \( X_{\text{min}} \), \( X_{\text{min}} \) is the lower level of the input process parameter, \( X_{\text{max}} \) the upper level of the input process parameter. Corresponding values are shown in Table 2. The central composite design matrix is prepared which consists of 28 degree of experiments. Dependency is on the number of input process parameters (k). Consists of 16 factorial designs (2k), 8 star points (2k) and 4 center points. Value of K and center points must be identical or depend on designer in order to find out the error in the model. The final design matrix consists of 28 trials as given in Table 3.

### Table 2. Corresponding values of operational parameters

| Welding process parameters       | Notation | -2  | -1  | 0   | 1   | 2   |
|----------------------------------|----------|-----|-----|-----|-----|-----|
| Open Circuit Current in Ampere   | I        | 160 | 180 | 200 | 220 | 240 |
| Wire Feed Rate cm/min            | F        | 9.5 | 10.5| 11.5| 12.5| 13.5|
| Gas Flow Rate lit/min            | G        | 16  | 17  | 18  | 19  | 20  |
| Welding speed mm/sec             | S        | 4   | 4.5 | 5   | 5.5 | 6   |
| Welding Voltage in volt          | V        | 23  | 24  | 25  | 26  | 27  |

### 2.4 Results of Experimentation

25 experiments are conducted on piece of AA7075 T6 grade. The experimentation are done for two pass weld joint on piece using aluminium alloy 5356 with 1.2 mm and thickness 10 mm filler wire rod diameter. In less passes material is filled in the groove. Experimentation is done under the shielding of oxygen and argon gas mixture. The rate of flow of argon and oxygen gas mixture is kept in 16–20 L/min range. The welded plates after experimentation are shown in Fig. 4. The transient temperature distribution into the plate due to conduction mode of heat transfer at different time intervals also due to convection mode of heat transfer at different time interval is finding out by using ANSYS workbench 14.5.

### Table 3. Design Matrix (Central Composite)

| Experiment No. | Wire Feed Rate F | Welding Speed S | Welding Current (I) | Gas Flow Rate (G) |
|----------------|------------------|-----------------|---------------------|-------------------|
| 1              | -2               | -2              | -2                  | -2                |
| 2              | -1               | -1              | -2                  | -1                |
| 3              | 0                | 0               | -2                  | 0                 |
| 4              | 1                | 1               | -2                  | 1                 |
### Table 4. Experimental Results & Validation

| Experiment No. | Voltage in volt | Current in ampere | Wire Feed Rate in mm/min | Gas Flow Rate in lit/min | Welding Speed in mm/sec | Width in mm | Height in mm | Penetration in mm |
|----------------|-----------------|-------------------|--------------------------|--------------------------|-------------------------|-------------|--------------|-------------------|
| 1              | 23              | 160               | 9.5                      | 16                       | 4                       | 15.2        | 3.1          | 8.9               |
| 2              | 24              | 160               | 10.5                     | 17                       | 4.5                     | 15.3        | 3.4          | 8.8               |
| 3              | 25              | 160               | 11.5                     | 18                       | 5                       | 15.25       | 3.45         | 9.1               |
| 4              | 26              | 160               | 12.5                     | 19                       | 5.5                     | 15.4        | 3.55         | 9.2               |
| 5              | 27              | 160               | 13.5                     | 20                       | 6                       | 15          | 3.9          | 9.3               |
| 6              | 26              | 180               | 9.5                      | 17                       | 5                       | 15          | 3.8          | 9.4               |
| 7              | 27              | 180               | 10.5                     | 18                       | 5.5                     | 15.2        | 3.7          | 9.45              |
| 8              | 23              | 180               | 11.5                     | 19                       | 6                       | 15.6        | 3.9          | 9.5               |
| 9              | 24              | 180               | 12.5                     | 20                       | 4                       | 15.7        | 3.9          | 9.6               |
| 10             | 25              | 180               | 13.5                     | 16                       | 4.5                     | 15.9        | 3.7          | 9.7               |
| 11             | 24              | 200               | 9.5                      | 18                       | 6                       | 16.1        | 4            | 9.75              |
| 12             | 25              | 200               | 10.5                     | 19                       | 4                       | 16.2        | 4.2          | 9.6               |
| 13             | 26              | 200               | 11.5                     | 20                       | 4.5                     | 16.35       | 4.3          | 9.8               |
| 14             | 27              | 200               | 12.5                     | 16                       | 5                       | 16.25       | 4.2          | 9.9               |
To find out optimized input process parameters which affects bead geometry (bead width, bead height, bead penetration) multiple regression analysis for fit model and optimize response MINITAB 17.3.1 is used.

**Table 5. Optimization Report (Bead Width Vs. Input Process Parameters)**

| Experiment No. | Voltage in volt | Current in ampere | Wire Feed Rate in mm/min | Gas Flow Rate in lit/min. | Welding Speed in mm/sec | Bead Width in mm | Bead Width in mm |
|----------------|-----------------|-------------------|--------------------------|--------------------------|------------------------|-----------------|-----------------|
| 1              | 23              | 160               | 9.5                      | 16                       | 4                      | 15.2            | 15.04           |
| 2              | 24              | 160               | 10.5                     | 17                       | 4.5                    | 15.3            | 15.09           |
| 3              | 25              | 160               | 11.5                     | 18                       | 5                      | 15.25           | 15.14           |
| 4              | 26              | 160               | 12.5                     | 19                       | 5.5                    | 15.4            | 15.19           |
| 5              | 27              | 160               | 13.5                     | 20                       | 6                      | 15              | 15.23           |

**Table 6. Optimization Report (Bead Height Vs. Input Process Parameters)**

| Experiment No. | Voltage in volt | Current in ampere | Wire Feed Rate in mm/min | Gas Flow Rate in lit/min. | Welding Speed in mm/sec | Bead Height in mm | Bead Height in mm |
|----------------|-----------------|-------------------|--------------------------|--------------------------|------------------------|-------------------|-----------------|
| 1              | 23              | 160               | 9.5                      | 16                       | 4                      | 3.1              | 3.13            |
| 2              | 24              | 160               | 10.5                     | 17                       | 4.5                    | 3.4              | 3.27            |
| 3              | 25              | 160               | 11.5                     | 18                       | 5                      | 3.45             | 3.43            |
| 4              | 26              | 160               | 12.5                     | 19                       | 5.5                    | 3.55             | 3.61            |
| 10             | 25              | 180               | 13.5                     | 16                       | 4.5                    | 3.7              | 3.74            |
Table 7. Optimization Report (Bead Penetration Vs. Input Process Parameters)

| Experiment No. | Voltage in volt | Current in ampere | Wire Feed Rate in mm/min | Gas Flow Rate in lit/min. | Welding Speed in mm/sec | Bead Penetration PEXPT in mm | Bead Penetration POPTIMUM in mm |
|----------------|-----------------|-------------------|--------------------------|--------------------------|-------------------------|-----------------------------|-----------------------------|
| 24             | 23              | 240               | 12.5                     | 18.0                     | 4.5                     | 10.4                        | 10.36                       |
| 23             | 27              | 240               | 11.5                     | 16.0                     | 4.0                     | 10.5                        | 10.31                       |
| 22             | 26              | 240               | 10.5                     | 16.0                     | 6.0                     | 10.1                        | 10.26                       |
| 21             | 25              | 240               | 9.5                      | 20.0                     | 5.5                     | 10.6                        | 10.21                       |
| 20             | 26              | 220               | 13.5                     | 18.0                     | 4.0                     | 9.9                         | 10.11                       |

The experiments are conducted as per central composite design matrix to develop the mathematical models for showing the relationships between the output responses y (HB, WB and PB) and input parameters x (welding voltage, welding current, wire feed rate, welding speed and gas flow rate). The regression equation is used to describe the relationship between the response and the terms in the model. The regression equation is an algebraic representation of the regression line. The regression equation for the linear model takes the following form,

\[ y = b_0 + b_1 x_1 \]

The final mathematical models in uncoded form based on the ANOVA analysis are given below:

1. \[ WB = 13.07 + 0.01900 I + 0.1170 F + 0.0000 G - 0.0940 S - 0.0690 V. \]

2. \[ HB = -0.429 + 0.01305 I + 0.0680 F + 0.0390 G + 0.0300 S + 0.0110 V. \]

3. \[ PB = 5.10 + 0.01505 I + 0.0490 F + 0.0120 G + 0.0500 S + 0.0230 V. \]

3. Tensile & Hardness Properties

The tensile test is carried out on work piece as per the ASTM E8 standards. Tensile test shows strength as well as ductility of material under tensile load. The test is conducted on 28 specimens which is prepared under different input process parameter. The following result is obtained from test. Mechanical properties i.e. UTS, elongation increases at the weld joint and hardness at the weld region decreases.

Figure 4. Samples after the experimentation
4. Transient thermal analysis of AA7075 T6 weld joint

The characteristics of the weld joint are affected by the flow & distribution of heat during welding. Size of fusion is also depending on flow rate of heat. The distribution of temperature is the key in changing the weldment properties. Because of cooling process/heating process thermal stresses gets induced and due to variable temperature gradients transient stresses gets induced. Temperature stresses with Mechanical one collectively used for design of components. Basically there are 3 heat transfer modes: conduction, convection and radiation. The heat rate in conduction mode of heat transfer is directly proportional to the plate area & inversely proportional to the plate length, means cross section is smaller, heat rate is faster, and vice-versa. Convection means transfer of heat because of motion of fluid. There are two types of convection forced and free. In FEM, convection is considered as a boundary condition and temperatures of plate surface are unknown quantity. Radiation is transfer of heat through an either vacuum or through the air. Heat transfer due to radiation and convection will happen simultaneously or separately between two surfaces.

The analytical study of residual stresses which is induced due to temperature is done. Simulations are done on welded plate having size of 125 mm × 100 mm × 10 mm with 600 groove angle and welded with each other by use of GMAW process. The height of the semicircular weld joint is taken as 2 mm. Three dimensional model is developed as shown in Fig.5. The material density is considered constant within range of working temperature and it is 2,803 kg/m3, specific heat is taken as 960 J/(kg.K), young’s modulus of elasticity is taken as 71.4 GPA and poison’s ratio is taken as 0.3. The thermal properties of AA 7075 T6 are used. The model is used to solve a problem of 3 dimensional transient or steady state thermal analysis. If the model consists of conducting solid element then it also needs to be analyze structurally. The mesh model developed with meshing size 1 mm is shown in Fig.6. The temperature boundary condition of the model means the difference in temperature at the two locations v: at the middle of the weld piece and at the end of the weld piece. The temperature in the centre i.e. at the centre weld joint is taken as 635°C (MP temperature of AA7075 T6) and the temperature at the end of the plate is taken as 28°C (ambient temperature).

The temperature boundary environment is converted in to the structural environment. The two plates are clamped by using clamping device at ends of the weld plate, and restriction to the motion is given in the y as well as z axis and permitted in the x axis during welding when stresses are occurred. In transient thermal analysis, temperature changes with respect to time at different locations in the weld piece. The distribution of the temperature in the weld plates at four various time intervals: 18 s, 22 s, 25 s and 30 s due to conduction & convections mode of heat transfer are shown in Fig. 7 and Fig. 8. Fig. 7 shows that maximum temperature exhibits at the weld zone and temperature further flow in the length of work piece in decreasing order.

The temperature flows to the end of the weld piece due to conduction mode of heat transfer. Figure 8 shows that the flow of temperature due to convection mode of heat transfers in the central part of the weld piece. The FEA thermal analyses are used to calculate residual stress occurred in the weld joint. (Refer Fig 9. a to c). The flow of the stresses is at top surface of the weld piece and various results

![Figure 5. Model developed](image_url)

![Figure 6. Meshing of the model](image_url)
obtained are plots along the surface. Also, the respective von-Mises equivalent stress distribution is plots to find out the final residual stresses. (Refer Fig.9d.) Residual stresses occurred along the x axis can be seen in Fig.9a.

Figure 7. Temperature distribution along plate (due to conduction at different time span) a at t = 18 s, b at 22 s, c at t = 25 s, d at t = 30 s

Figure 8. Distribution of temperature along plate (Due to convection at different time intervals) a at t = 18 s, b at t = 22 s, c at t = 25 s, d at t = 30 s
Figure 9. Residual stress developed: a Transverse stress along X, b Transverse stress along Y, c Transverse stress along Z, d Von-Mises stresses

The maximum tensile stress is seen at the welded zone part in comparison with the other part in the weld piece. Normal stresses in the direction of y axis shown in Fig.9b, the distribution of stress at the thickness of plate having a maximum compressive stress in comparison with other part. The stresses in the z axis are shown in Fig 9c. , the maximum compressive stresses are observed at the top surface of the weld joint. Values for Von Mises stress is at highest in weld join, while goes on decreasing minimally towards the bottom of joint. as shown in Fig.9d
5. Conclusions

1. Residual stress & Von-Mises stress is estimated. Temperature distribution flow for varied time intervals is estimated by transient thermal analysis. Whereas, spread of residual stress occurred as an effect of time dependent conduction and convection.

2. Welded zone exhibits maximum temperature and gradual movement across welded plates during conduction. However, central part is affected with convection.

3. Temperature plots with and without convections can be compared and it can be observed that convection has very less effect of on an average of 7 degrees centigrade temperature reduction on aluminum specimen.

4. Temperatures are not affected by convection much because heat transfer due to conduction is very high in case of aluminum when compared with convection and radiation.

5. Plots shows that von mises stress line is mostly contributed by the stress in longitudinal direction which is X direction.

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