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Gas Metal Arc Welding Input Parameters Impacts on Weld Quality Characteristics of Steel Materials a Comprehensive Exploration

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To be competitive, present-day manufacturing industries strive to optimize input process parameters to produce their products with the desired quality characteristics. From various manufacturing processes, metal joining is one of the key methods for joining a large variety of indispensable products including the production of an automotive body in white structures, assembly of heavy metal civil structures, nuclear installations, pressure vessels, aircraft, and spacecraft materials, etc. In order to get the level of quality requirement of welded components an optimized combination of welding parameters plays a significant role. However, the realizations of this optimum combination of welding input parameters for all processes in diverse conditions are a big challenge for the manufacturing industry. The current study presents a critical assessment of the various researches in the fields of gas metal arc welding (GMAW) of steel to create a descriptive picture of the effect of process variables and input parameters on weld quality characteristics. To realize this, intensive literature reviews and comparisons of different results have been made, and findings have been incorporated. Where there are differences in trends of parameter effects, proper explanations, and justifications have been drawn. As a result, it was found that arc voltage, welding current, wire feed rate, and travel speed affect the quality of the weld (mainly penetration, bead height, bead width, and heat-affected zone) significantly compared with other parameters considered in the context of this paper. This shows that the proper setting of the optimum combination of welding parameters specifically, arc voltage, welding current, wire feed rate, and travel speed yield the desired quality level of the weldment.

Keywords: GMAW, Welding Parameters, Weld Quality Characteristics, Steel Materials, Process Condition

1 Introduction

In the manufacturing and fabrication industries, fusion welding is among the most broadly utilized joining mechanisms and methods. The fusion welding process characteristics which influence majorly weld joints are the heat source intensity, the heat input rate, the methods used, and effectiveness of shielding gas to protect the weld from atmospheric contaminations [1]. There are several types of fusion arc welding processes based on the methods of heating metals in higher temperatures and thereby melting and welding them together. The process includes Laser welding, Arc welding, Induction welding, Solid reactant welding, and Oxy-fuel gas welding. Among these, the first and most commonly used kind of fusion welding process is arc welding which is used to join metals with intense heat generated from an AC/DC power supply [2, 3]. Under this phenomenon, there are many those certain processes, including stud arc welding (SW), Electroslag welding (ESW), Gas metal arc welding (GMAW), Carbon arc welding (CAW), Electro gas welding (EGW), Atomic hydrogen (arc) welding (AHW), Flux-cored arc welding (FCAW), Gas tungsten arc welding (GTAW), Magnetically impelled arc butt welding (MIAB), Plasma arc welding (PAW), Shielded metal arc welding (SMAW), and Submerged arc welding (SAW) [4]. Many experimental research findings revealed that GMAW is the most commonly used joining process preferred due to its versatility, reliability, high productivity, high efficiency, good weld quality, easy-to-realize automation, and low production cost [3, 5-7]. Due to the versatility and advantages of this process, this has been applied to many real-time industrial applications. [8-11]. Low alloy steels, high alloy steels, stainless steel, carbon steel, titanium, copper, nickel alloy, and aluminum are among the major essential metals welded by the GMAW [5, 12, 13].

The basic concept of GAMW is the melting and joining of various metals by an established arc between base metals and wire electrodes as demonstrated in Fig. 1 [3, 4, 14]. In this process, the continuous filler wire is drawn automatically by a wire feeder from a reel. Heat is largely focused on the welding arc from the tip of the melting electrode to liquefied weld pools [15]. Molten weld puddles and filler wire were sheltered by the shielding gas [16].

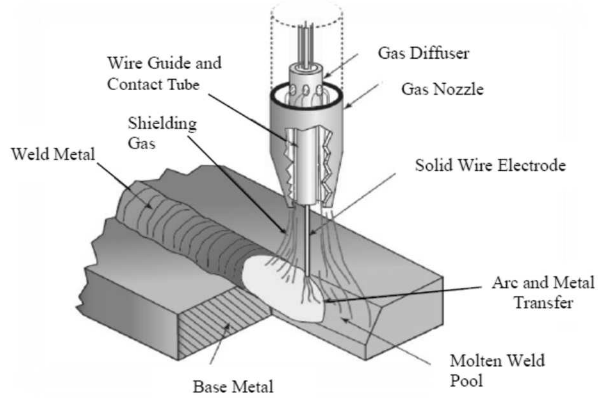

***Fig. 1** Schematic diagram of Gas Metal Arc Welding process*

The weldment quality characteristics are mainly portrayed by the heat-affected zone (HAZ), of weld bead geometry, penetration, microstructure, and mechanical properties [3, 5, 15, 17, 18]. In line with this, the quality level of the weld joint can be determined by many features such as; - surface imperfections and internal imperfections. Surface imperfections include lack of fusion, incomplete penetration, excessive convexity, excessive penetration, excessive asymmetry, excessive throat thickness, insufficient throat thickness, spatter, etc. Likewise, internal imperfections include cracks, porosity, inclusions, lack of fusions, lack of penetrations, etc. [19].

To characterize different welding input parameters and their impact on weld quality researchers have implemented several methods. These include the design of experiment methods, Taguchi method, factorial design, regression analysis, response surface methods, mathematical equations, artificial intelligence systems, etc. [3, 20-24]. Welding input parameters and their level (the process parameters' working capabilities) are selected based on different conditions and procedures including types of material, the function of the welded part, the strength requirement, etc. [5]. GMAW input process parameters are the most significant factors that influence the methods by which the electrode is transferred to a parental metal, weld bead geometry, cost of welding, and quality of weld [10, 21, 25, 26, 27]. GMAW is a comprehensive and multi-parameters mechanism wherein quality is paramount of welds affected by which input parameters are not known [28, 29]. The most significant tasks in this process are the selection of proper welding input parameters [5]. So, Srivastava and Garg [3] advised that intensive investigation of several MIG input process parameters is required to characterize the weld quality and their interdependence.

The scope of the study is to explain the major characteristics and impacts of robotic, automatic, and semi-automatic GMAW input process parameters on weld quality characteristics. Among the several input variables, arc voltage, welding current, wire feed rate, travel speed, contact tip-to-work distance (CTWD), shielding gas flow rate, electrode work angle, and heat input are considered to comprehend the level of effects of each factor on weld quality characteristics of steel materials. The complete welding process, materials, and welding parameters cited from various works of literature are presented in Table 1.

2 Effects of welding parameters on weld quality characteristics

2.1 Effect of arc voltage

Arc voltage is an amount of electric potential that exists on a small gap between the metal to be welded and the end of the electrode which causes an electric discharge across the gap. The voltage drops within the electrode extension beyond the contact tip are included [30]. Arc voltage is a major input parameter directly proportional to the arc length and is used in order to create a stable arc [31]. Various studies revealed that arc voltage is one of the critical variables in arc welding process control [30, 32]. The arc voltage is determined mostly through arc length, which would be determined through the electrode diameter [5]. Depending on the process inclination, an excessively high arc voltage leads to arc instability, spatter, undercut, porosity, erosion, and sprinkling depending on the inclination of the process [10, 32]. There are some quality characteristics affected by the arc voltage. These are:

- **Penetration:** Arc voltage has a remarkable influence on monitoring the arc force which controls the primary depth of penetration. The greater arc force at higher arc voltage pushes the melted metal toward the bottom of the weld pool and rises the primary penetration region up to a certain level [28]. The arc voltage impacts the arc pressure/force that in turn influences the penetration depth. When arc voltage increases, the melting of the parent metal and weld penetration increases [5, 8]. However, arc voltage influences the depth of penetration not much as welding current influence [21, 26]. The influence of arc voltage was less sensitive to penetration than to other bead shape parameters [14, 15].
- **Bead height:** Arc voltage is more suitable in the control of bead height. The variation of arc voltage causes big changes in bead height in the meantime the sensitivity of arc voltage

on bead height is much greater than that of current and travel speed [15]. Low arc voltage produces narrower beads with greater convexity [28]. The relationship described by different authors entails that bead height decreases when an arc voltage increases; because the same volume of weld metal is deposited at a constant wire feed rate [8, 15].

- **Bead width:** Arc voltage maintains arc dome stability and controls the arc width; rising welding voltage is increased arc width, which outcomes in bead width improvement [28]. Arc voltage is more suitable for controlling bead width within which variations cause large improvements. An increase in welding voltage increases arc length and the size of droplets, resulting in a flatter and wider weld bead [5, 8, 9, 10, 15, 24].
- **Heat affected zone:** HAZ is a non-melted zone of parent material and achieved different metallurgical properties other than the base materials. Arc voltage is crucial in boosting HAZ because it can produce more heat input and a compressive weld pool [33]. The influence of arc voltage was observed in HAZ due to the variation in the material morphology; as the arc voltage increases, the HAZ width increases [27, 28].

2.2 Effect of welding current

Welding current plays a main role in arc heating and key operating parameter for monitoring the melting quantity. High-level current results in more heat input at the electrode, melting the filler wire nearer and transferring more amount of heat to the workpiece to generate a bigger weld pool [31]. Welding current has a robust positive direct relationship and is the first and most significant effect among all bead geometry characteristics since that gets to decide the wire feed rate, heat input of welding, melted base metal, weld fusion area, and amount of deposited metal [23, 30, 34]. Gosh, et al. [25] studied the percentage of elongation and the maximization of ultimate tensile strength obtained in the optimal parametric condition (the current is 124A, the gas flow rate is 10l/min, and the nozzle-to-plate distance is 9mm). It was found that welding current has a more influential parameter than gas flow rate followed by the nozzle-to-workpiece distance. The quality characteristics are mainly affected by the welding current explained in the following section.

2.2.1 Penetration

An increase in the level of welding current raises the depth of penetration. Thus, if the current is too high, there will be a larger amount of heat generated resulting in excessive deep penetration that can potentially waste filler metal and cause burn-through and undercut. When using too low a welding current for a given electrode yields poor penetration [8, 21, 23, 35]. Karadeniz et al. [26] studied Erdemir 6842 steel sheets using 2.5mm thickness and a filler wire was a G3Si 1 (SG2) electrode with a diameter of 1mm, and the outcomes showed that perhaps the depth of penetration raises linearly with a rising welding current between 95A and 115A, with the average depth of penetration continuing to increase to 0.0225mm for a 1A rise in welding current. The influence of current on penetration is nearly 2.5 times higher than that of welding speed and arc voltage. The average arcing current has a robust effect on the amount of depth of penetration [30].

2.2.2 Bead height

Bead height is one of the characteristics of quality weld affected by current. Bead height increase with an increase in mean current at fixed thermal pulse frequency [36].

2.2.3 Bead width

The width of the welded bead depends upon welding processing variables including welding current, arc voltage, travel speed, electrode size, gas flow rate, contact tip to workpiece distance, etc. With increasing welding current, the width of the weld bead grows [9, 36].

2.3 Effect of wire feed rate

Wire feed rate refers to the rate at which filler wire is fed through into the weld joint, which has a major effect on the amount of current and weld penetration. The convexity index is affected by the wire feed rate; a positive rate of the wire feed coefficient has a positive impact on the convexity index [28]. An excessive increase in wire feed rate results in an excess of filler metal, which causes improper adherence to the weld zone and an increase in heat input due to a larger number of short circuits formed at the same time [32]. Srivastava and Garg [3] optimized welding parameters (wire feed rate 4.5m/min, arc voltage 32V, gas flow rate 10.3lpm, travel speed 160mm/min) to obtain 0.891mm bead height, 7.53mm bead width, and 4.02mm depth of penetration. As the results of an investigation, the significance of input process parameters to weld bead determination is wire feed rate followed by voltage and travel speed. The major impacts of wire feed rate on weld quality characteristics are discussed in the following section.

2.3.1 Penetration

Wire feed rate affects the extent of depth of penetration considerably. The deposition rate was effectively stated as a role of numerous parameters and mostly determined by wire feed rate [28]. Increasing the rate of wire feed deposits more molten metal and increases the depth of penetration [5, 8, 14]. A higher feed rate increases the amount of heat input in the weld pool zone which in turn results in an increased depth of penetration [34].

2.3.2 Bead height

The rate of wire feed is one of the key input parameters that affect bead height too. The wire feed rate plays a critical role in predicting weld area, accounting for 33.48% of the variation within linear a model, Even though welding wire acts as filler metal, rates of wire feed are positively found to correlate to bead height and a higher wire feeding rate results more welding filler materials per second [14].

2.3.3 Bead width

According to Kamble and Rao [5,] enhancing the rate of wire feed results in a rise in bead width because of a rise in the amount of material deposited inside the weld joint. An increase in the rate of wire feed leads to a rise in joining temperature, and liquefying a large amount of filler wire to the weld pool leads to a rise in bead width [32]. The relationship among the rates of wire feed and bead width is not statistically significant, but the result is a positive correlation [14].

2.3.4 Heat affected zone

An increase in the level of wire feed rate results in a more comprehensive weld pool and heat transfer within the weld zone, which results in coarser grains [33]. When a welding speed of 10mm/s, an arc voltage of 23.5V, and a wire-speed rate of 12.6m/min are used for LNE 700 high-strength steel material of 4.5mm thickness and 1mm diameter filler metals, the smallest (22mm^2) HAZ is obtained [27]. Due to the diminishing effect on the width of HAZ, the width of HAZ is stated as a function of the wire feed rate [28].

2.4 Effect of travel speed

The distance traveled demonstrates the length of time that weld materials are deposited from arc initiation to termination. The linear rate that an arc travels along the weld joint is defined as the speed of travel [6]. It plays an significant role in the quantity of heat generated into the welded joint per unit length of the weld. The travel speed is among the most challenging variable to anticipate inside the weld-making procedure [23], and it has a significant effect on the quantity of heat generated in the joint per unit length of the weld (Phillips, 2016). Excessive travel speed leads to a shortage of filler metal accumulation at the parent metal (lower metal deposit in the bead), resulting in inadequate welding beads. Also, because the arc exerts its effects on the parent metal, the quantity of thermal energy transmitted from the arc to the parent metal reduces as travel speed increases [10, 32].

Kumar et al. [18] studied the effect of welding variables and parameters on bead width and height, weld penetration, and HAZ. The optimal bead width of 6.42mm, bead height of 1.78mm, welds penetration of 2.92mm, and HAZ 5.26mm was obtained in the setting of welding parameters current 170A, arc voltage 27V, and welding speed of 52cm/min, the percentage contributions of welding speed, voltage, and welding current on weld bead geometry were 90.08%, 4.55%, and 0.66% respectively. The speed of travel along the weld joint impacts the bead shape, depth of fusion, heat input, and weld bead appearance, all of which impact the microstructure of the weldment [9, 14, 15]. Weld quality characteristics that are affected by travel speed are incorporated in the following section.

2.4.1 Penetration

Weld bead penetration decreases when the welding speed increases due to decreases the time it takes the arc force to penetrate the surface of the parent material including the volume of material deposited decreases [5, 9, 14, 15 22]. Besides that, when the travel speed is reduced, the concentration of heat input rises, resulting in greater penetration [16]. When traveling at a high speed, the arc forces, arc heat, and droplet impingement are not concentrating on the molten weld pool; the downward molten pool is smaller, the downward flow pattern is relatively weak, and the quantity of molten weld pool that penetrates the root gap is relatively small [37].

A study conducted on Erdemir 6842 steel having 2.5mm thickness using a G3Sil wire electrode of 1mm diameter attains a relationship that conforms to an increase in the depth of penetration. In this case, the optimum values of travel speed, current, and voltage for higher possible penetration were reported as 60cm/min, 115A, and 26V respectively. Between 40 and 60cm/min, the penetration increases from 0.03 to 0.08mm. After the optimal point, the value decreased [26]. Again Karadeniz et al., [26] explored and obtained the optimal weld penetration of 4.53mm with optimum combinations of welding parameters (travel speed 60cm/min, welding current 110amp, and wire diameter 1.2mm). Travel speed contributes 46.61%, welding current contributes 21.24%, and wire diameter contributes 27.25% to the depth of penetration. The results showed that travel speed has the greatest influencing factor on penetration depth.

2.4.2 Bead height

Travel speeds have a critical effect on bead height. The size of the weld pool and the rate of wire deposition decreases as travel speed increases, which means bead height decrease, Reduction in bead height due to the weld pool size was affected by the cooling rate [8, 14]. With increased travel speed, less filler wire per unit length is deposited on the parent materials resulting in lower bead height [5, 9].

2.4.3 Bead width

There is an inverse correlation between the speed of travel and bead width; an increase in arc-travel rate decreases the size of bead width [5, 8, 14]. It can be observed that bead width becomes higher as travel speed decreases [38]. When the travel speed increase from 5cm/min to 7cm/min bead width also increases from 7mm to 8mm, an increase in welding voltage creates a longer arc and increases the size of droplets, which in turn, causes a wider and flatter weld bead [24].

2.3.4 Heat-affected zone

Lermen et al., [27], well-defined HAZ as a function of travel speed whereby they confirmed that 'on average the HAZ decreased when the speed of travel increases'. There are great contributions of travel speed on cooling rate and heat affected zone throughout and after welding, as the depth of penetration rises with decreasing travel speed, the cooling rate determine the final metallurgical structure of the weld zone [22]. In agreement with all the above, Tagimalek et al., 2021 [33], underscored that 'as travel speed increases the HAZ decreases significantly'.

2.5 Effect of contact tip-to-work distance

Contact tip-to-work distance (CTWD), the gap between both the end of a contact tip and the workpiece surface, is a significant welding parameter that mainly affects the amperage, arc voltage, shielding gas used as well as metal transfer mode [39]. Gyasi et al., [22] Gyasi et al., (2017), noted that the CTWD controls the welding current as a function of the arc length, the control characteristics portrayed and finding showed that when the CTWD rises the welding current decreases, and when the CTWD decreases the welding currents increase. Hence, CTWD and the current have an inverse relationship; CTWD significantly influences the amount of arc length. Welding process stability and weld quality were sensitive to CTWD [40]. The quality characteristics of weldment affected by CTWD are included in the following section.

2.5.1 Penetration

The relationship between depth of penetration and CTWD is linearly proportional, penetration increases with an increase in the nozzle-to-workpiece distance [8]. The increase in the CTWD means an increase energized length of the electrode before the fusion of the electrode occurs, due to more resistance in the conductor (the Joule effect) [39]. However, other works of literature incorporated a finding that contradicts the above; Higher CTWD reduces the arc pressure and decreases penetration; because, when CTWD increases the length of electrode extension increases, and an increase in resistance to the flow of current consequences in a decreasing welding current resulting in arc pressure decreased [28].

2.5.2 Bead height

The relationship between CTWD and bead profile has been described in various works of literature. Weld bead profiles are sensitive to CTWD [40]. Greater CTWD diminishes arc pressure and increases the reinforcement height [28].

2.5.3 Bead width

The aspect of the association between bead width and CTWD seems to be direct proportionality. The width of the weld bead rises with the increasing CTWD [9]. Higher CTWD, on the other hand, decreases arc pressure and decreases bead width [28].

2.5.4 Heat-affected zone

In the steel welding processes, the HAZ region is very critical due to metallurgical and allotropic weld transformations which impact mechanical characteristics [41]. The width of HAZ is defined in terms of CTWD, Thus, CTWD has a positive impact on the width of HAZ; higher CTWD reduces the amount of width of HAZ [28]. Increasing the gap between the end of the filler wire and the parent materials can reduce the heat-affected zone [33].

2.6 Effect of shielding gas flow rate

The flow rate of shielding gas is one of the welding input variables that affect the geometry/profile of the weld bead for the reason that the gas flow pressure allows the distribution or well spreading of molten materials [32]. The value of hardness increases as the rate of gas flow increases because of the high velocity of its arc created (melted more filler metal) and fill groove of weld bead [5]. Microhardness values change throughout the weld bead varying by shielding gas flow rate [42). Uncontrolled shielded of the weld pool and arc occurred due to an excessive gas flow rate that causes turbulence [21]. The right flow rate of shielding gas is important such as offering appropriate safeguards to it the welding region throughout the stages of heat generation, liquidation, and solidification. A too-low gas flow rate will result in porosity and excess spatter development due to the insufficient shield of the arc area. In contrast, too high a gas flow rate will result in poor penetrating and/or porosity owning attributable to instabilities within the gas column [43]. The quality characteristics of a weld affected by the shielding gas flow rate are included in the following section.

2.6.1 Penetration

Gas flow rate is one of the influencing parameters that affect the depth of penetration [21] (. If the gas flow rate is too high penetration will be poor [43]. Increasing the gas flow rate increases the depth of penetration [5]. On the contrary, other works of literature noted that gas flow rate does not affect weld penetration [8].

2.6.2 Bead height

A rise in the rate of shielding gas flow increases the fusion area and height of the bead because it produces high-velocity plasma [5]. When the velocity of the gas flow increases an increase in bead height is expected due to low imparting pressure [8].

2.6.3 Bead width

Its connection between the rate of gas flow and the bead width follows positive proportionality. Thus, a rise within the rate of gas flow melts more filler metals because of high velocity and increases bead width [5, 9].

2.6.4 Heat-affected zone

The thermal property occurring in the solidified weld, shielding gas flow rate plays a significant role [43]. As verified, Like a higher specific heat capacity, lower thermal expansion, and worthy thermal conductivity beneficial behaviour exhibits with a lower shielding gas flow rate than a higher shielding gas flow rate. Reducing the rate flow of shielding gas within identical heat input raises the heat transfer efficiency factor and a lesser degree of distortion. At larger flow rates of shielding gas, thermal expansion/extension of coefficients is greater through temperature variety series. In addition, its leads to the highest volumetric contraction and expansion inside a weld metal and larger residual stress and HAZ within the structure of the material [42, 43].

2.7 Effect of electrode work angle

The electrode work angle is the relationship among the center of the electrode and the surface of the workpiece. The literature revealed that macrostructure, microstructure, arc shape, and mechanical properties are sensitive to the traveling angle of the torch and electrode work angle (position of the torch), the rate of deposition is lower at the torch is offset/incorrect placement through a cross-section to the groove. Mostly, within fillet weld, a welding position like down-hand horizontal (2F) has projected which an angle of torch within respect towards the position of the torch must be 45–50° and the traveling angle of the torch would be 10–15° in the welding direction [22]. Electrode work angle has a major effect on determining leg length (creating an asymmetry) by altering the angle of the torch proceeding to a vertical plane of the welding direction; it has a negative linear relationship with leg length [23].

2.7.1 Penetration

Torch angle inconsistencies result in insufficient fusion and undercut, mostly in the vertical structure component of the fillet weld. This occurrence leads to quality problems and a lack of penetration between the vertical plate and the base metal [22]. Penetration declines with an increase in electrode-to-work angle [8, 23].

2.7.2 Bead height

Work angle is one of a parameter of welding that impact on penetration and bead of weld shape [30]. The weld bead geometry (like, bead height and bead width) influences the mechanical properties of the weld. Weld bead height/reinforcements are influenced by torch angle [8].

2.7.3 Bead width

Changing the inclination angle and direction of the torch and the amount of power per unit length of the weld influences the behavior of the weld shape. As soon as welding through the electrode slanted bestowing toward its workmanship motion/movement, an arc penetrates deeper and thickness occurred by the zone of fusion decrease and, while at an opposite inclination width of the weld bead increases and the depth of penetration decreases [44].

2.7.4 Heat-affected zone

Torch angels exhibit a significant effect on the heat-affected zone [22]. For the study, the influence of electrode inclination S235 steel plate numerical analysis was shown, and the padding of a rectangle element (0.4m x 0.6m) having a thickness of 0.03m was investigated to suit the requirements of the semi-infinite modelling of a body. In this situation, the inclination of the electrode work angle causes a reduction in the depth of its action. An electrode-to-work angle of 60º inclinations produces broader but shallower HAZ at substantially higher temperatures than an angle greater than 90º. The dimensions of the HAZ are intermediate when the angle is equal to 120º, while the narrowest and the deepest HAZ are acquired for electrode work angle is less than 90º [44].

2.8 Effect of heat input

The quantity of electrical energy expressed as energy per unit length is referred to as heat input. Heat input is determined principally by current, voltage, and travel speed [31]. Heat input affects the way molten filler material transfers, arc stability, weld bead profile development, solidification mechanism, and metallurgical transformation which influence the morphology and efficiency of the welded metal [22, 45]. Heat transfer to the workpiece has a substantial impact on weld fusion, and a linear relationship occurs between heat input and fusion area [30,53]. In line with this, too low heat input makes inadequate melting of weld deposit, but a big weld pool is generated due to excessive heat input, which causes metal flow in front of the arc deterring the melting of parent metal [21]. The quantity of heat input controls the radius of the arc, and the effective radius of the arc is the primary essential element for the creation of weld bead penetration [46]. The next section describes the quality features of welds that are affected by heat input.

2.8.1 Penetration

Penetration depth has linear relationships with heat source parameters. The heat input provided to the parent metal per unit length which turn is determined by that of the welding variable and parameters of the process, applying more heat input per unit length to the parent metal causes more melting of the parent metal which results in more depth of penetration [8, 47]. Larger heat input (i.e., more heat deposited on the surface of the parent metal) leads to more penetration [16]. A More amount of heat applied to the weld pool region implies a deep penetration [34]. If the heat input has become too insufficient, the possibility of fusion failure increases [48].

2.8.2 Bead height

Bead height is one of the weld quality characteristics and it is mostly determined by the amount of heat input and the mode of metal transfer. It plays a significant role to form weld bead geometry; higher heat input yields low reinforcement [49-52].

2.8.3 Bead width

The variance in weld bead width is caused by differences in temperature distribution between the parent material and filler wire. Whenever the parent material got lower heat input per unit length, the quantity of melting of base metal was reduced and the deposited amount of filler electrode decreased, which resulted in a smaller weld bead [8]. A larger heat input resulted in a broader weld bead [49-51]. Welding fusion width has directly related to heat source parameters [47]. The quantity of heat input in the weld zone has a strong linear connection with bead width [30].

2.8.4 Heat affected zone

The width of the HAZ is shown as a function of heat input. More heat input results in a coarser microstructure in the weld zone [45]. A larger heat input might cause serious destruction in the HAZ, which creates a weak spot in the welded materials [41]. At greater heat input, the primary ferrite, polygonal ferrite, and ferrite side morphology of HAZ grew significantly. When the heat input is significant, the width of the HAZ grows because the grains become coarser as the heat input rises. In principle, HAZ and grain size of weld metal are mostly impacted by heat input and rise as heat input rises [28].

Tab. 1 *Welding process type, materials and consumables, and welding parameters cited from various literatures*

Authors and year	Welding process type	Materials and consumables	Welding parameters
Adak et al., [28]	Universal MIG/MAG machine	– Mild steel plate of 150mm×150mm×9mm having 0.15% carbon – Uncoated electrode wire 1.2mm diameter. – Shielding gas mixture 70% Ar and 30% CO_2.	– Arc Voltage (AV):19.8 and 24V – Wire feed rate (WFR): 3.5 and 5.5m/min – Contact tip to work distance (CTWD): 15 and 25mm – Travel speed (TS): 250 mm/min – Angle maintained at 20°
Chaudhari et al., [12]	Autogenously mode of GMAW process.	– SS316L stainless steel plate, 100mm×50mm×6mm. – Shielding gas Ar+CO_2 – Two fluxes used Cr_2O_3 and SiO_2	– Welding current (WC): 150-180A – AV: 20-24V – TS: 150-180mm/min – Shielding gas flow rate (SGFR): 15 l/min.
Cho et al., [46]	GMAW, TPS 2700 Trans-pulse synergic welding machine.	– Mild steel SS400 – Wire filler ER70S-6 diameter 1mm. – Shielding gas Ar and 5% CO_2	– CTWD: 15mm – WFR: 7m/min – TS: 0.8m/min – SGFR: 20 l/min
Dagostini et al., [41]	Automatic GMAW system with Panasonic robotic arm TM-1400WG III	– API 5LX70M steel, size 175mm×85mm×16.5mm – Filler metal WI.M 2594, electrode diameter 1.2mm. – Shielding gas Argon+20% CO_2	– AV: 18.5V – TS:: 1.23, 1.48, and 1.85 mm/s – Heat inputs: 3.0, 2.5, and 2.0kJ/mm – SGFR: 15 L/min – Welding frequency: 0.5Hz
Filho and Fer-raresi, [39]	MIG/MAG welding process, and LAPROSOLDA gas mixer	– Parent metal Ferritic stainless steel bi-stabilized with niobium and ti-tanium – Filler wire used Ferritic stainless steel ER430. Wire diameter 1.2mm. – shielding gas (pure Ar , and Ar with mixed O_2 and CO_2)	– Shielding gases (Ar; Ar + 4% O_2, Ar + 2% O_2, Ar + 8% CO_2, Ar + 4% CO_2 and Ar + 2% CO_2) – CTWD: 12, 14, 16, and 18mm – Constant AV: 20V – WFR: 5.3m/min – TS: 20cm/min – SGFR: 14l/min.

Authors and year	Welding process type	Materials and consumables	Welding parameters
Ghosh et al., [25]	MAG welding machine, K-400MIG	– Stainless steel AISI 409 (Ferritic) of size 100×65×3mm – Austenitic electrode wire AISI 316 L. diameter of 1.2mm.	– WC (A): 100, 112, 124 – SGFR (l/min): 10, 15, 20 – Nozzle to plate distance (mm): 9, 12, 15
Gupta et al., [8]	GMAW process	– stainless steel (Ferritic) plates of SS 409L dimensions 200×50×3mm – Austenitic stainless steel filler wire ER304L diameter 1.2mm. – Shielding gas type - pure argon	– TS: 300, 400, 500mm/min – WC: 130A – AV: 20V – SGFR: 18l/min – Root gap of 1.2mm
Hackenhaar et al. [38]	Welding robot MA1400A composed of Fronius Trans Puls Synergic 4000R welding machine.	– AISI 1010 steel 250mm×150mm×6.35mm. – Electrode diameter 1.2mm, AWS ER70S-6 – Shielding gas mixture of Ar+25% CO_2	– WRF: 3.5 4.5 5.5m/min – AV: 18, 20, and 22V – TS: 4.0, 5.5, 7.0mm/s – SGFR: 15l/min
Ibrahim et al., [35]	B4 welding robots, OTC ALMEGA AII	– Mild steel plate dimension of 100mm×100mm×6mm – Electrode wire 1.2mm diameter (AWS classification ER70S-6) – Shielding gas 100% CO_2	– AV: 22, 26 and 30V – WC: 90, 150 and 210A – TS: 20, 40 and 60cm/min – Torch angle: 5° – Nozzle to work distance:12mm
Kamble and Rao [5]	GMAW semiautomatic air cooling machine 3-phase, 50Hz, 300A.	– AISI321 stabilized austenite stainless steel plate size 150mm×120mm×10mm – AISI308 grade filler wire – Argon and oxygen mixture	– AV: 27, 28, 29, 30 and 31V – SGFR: 16–20l/min – Welding torch is fixed 90˚ to the workpiece – V-groove prepared at 30˚
Karadeniz et al., [26]	Welding robot capacity of 0-500A and 0-50V ranges. DAIHEN, DR Series ARK ROBO 1100	– Erdemir 6842 steel specimens having 60mm×30mm×2.5mm – G3Si 1 (SG2) wire electrode of 1mm diameter – Shielding gas is 82wt% Ar+18 wt% CO_2 mixture	– WC: 95, 105, 115A – AV: 22, 24, and 26V – TS: 40, 60 and 80cm/min – Root gap fixed as 0.8mm – Welding torch is centered
Kim, Son, Kim, et al., [15]	Robotic CO_2 arc welding process	– Mild steel AS 1204 specimen dimension of 200mm×75mm×12mm – SS400 using steel wires of 1.2 diameters – Shielding gas Ar (80%) and CO_2 (20%) composition.	– AV: 20, 25, 30V – TS: 250, 330, 410 mm/min – WC:180, 260, 360A
Kumar et al., [18]	INVA MIG 400 welding machine	– AISI 1020 carbon steels specimens having 200mm×50mm×6mm – ER 70 S-6 wire electrode having 0.8mm diameter – CO_2 shielding gas used.	– AV: 26, 27 and 28V – TS: 42, 47, and 52cm/min – WC: 160, 170, and 180A
Lee and Rhee [23]	Welding robot system	– Base metal mild steel with 90mm× 100mm×60mm – Wire diameter is 1.2mm. – Shielding gas 100% CO_2	– SGFR: 15l/min – CTWD: 15mm
Lee et al., [50]	Robot gas metal arc welding	– SGAPH590 and SGAPH440 steel material of 2.3mm and 2.0mm×80mm×140mm – Filler wire ER70S-3 1.2mm diameter. – Shield gas Ar+10%CO_2	– WC: 170 and 200A – Travel angle 0, 17.5 and 35° – SGFR: 20l/min

Authors and year	Welding process type	Materials and consumables	Welding parameters
Lermen et al., [27]	Robot gas metal arc welding process	– High strength steel, LNE 700 size 50mm×100mm×4.5mm. – wire diameter of 1mm OK Aristorod TM 79 – Shielding gas mixture argon (82%) and CO_2 (18%).	– AV: 23.5, 26.5 and 30V – TS: 8.3, 9.2 and 10mm/s – WFR: 12.6, 14.2 and 16m/min
Ley et al., [7]	Automatic welding process	– DH36 steel plate dimension 150mm×500mm×8mm, – Filler wire 1.2mm diameter Nittetsu SF-1A. – Shielding gas two supplies premixed Ar+20% CO_2 and pure He.	– Gas delivery methods – Ar/CO_2 constant – He constant – Ar/CO_2/He (Alternating at 2, 4, 6, 8 Hz). – SGFR: 5, 10, 15l/min – TS: 3.2mm/s – Constant standoff distance 10mm – WC: 210A – AV:24.7V
Park et al., [37]	Pulsed GMAW process, trans-pulse synergic mode, TPS 2700 welding machine.	– Mild steel SS400 10-mm-thick specimen. – Wire ER70S-6, 1mm diameter – Shielding gas Ar+5% CO_2	– TS: 18 and 33cm/min – WFR: 7m/min – SGFR: 20l/min – CTWD: 17mm – Root gap size 0, 1 and 2mm – Average WC: 159A – Average AV: 20V
Pérez Pozo et al., [32]	A KUKA KR 125/2 robot arm, incorporates an ESS welding machine	– AISI-SAE 1020 structural Steel 300mm×50mm×5mm. – Filler material diameter 1.2mm, AWS: ER-70S- 6/ER-48S-6. – Shielding gas mixture of Ar and 20% CO_2	– AV: 65, 70 and 85V – TS: 15m/min – WFR: 4m/min – SGFR: 16l/min – Swinging length 2mm
Ramos-Jaime et al., [14]	Robot gas metal arc welding	– Base material Steel 1018 (4,3/4" ×1,1/2" × 1/2") – Electrode Steel LS-69 (0.035") – Shielding gas 99.999 %Ar.	– WFR: 6.35, 7.62, 8.89 m/min – AV: 23, 25, 27V – TS: 0.007, 0.009, 0.011m/s – Gas pressure 40 PSI – Torch angle 90°
Rizvi and Tewari, [42]	GMAW process	– Structural steel plates IS 2062 size of 300mm×120mm×10mm – ER 70S6 filler metal – Shielding gas Ar+25% CO_2	– AV: 25, 26 and 27V – WC: 198, 200, 206, 208, 220, and 230A – SGFR: 10, 15 and 20l/min
Saha et al., [49]	GMAW process	– Low alloy steel, E350 – Wire electrode austenite stainless steel (316) – Shielding gas 100% CO_2	– WC: 120, 140, 150, 160, 170, 180, 190, 200 and 220A – AV: 22, 23, 24, 25, 26, 27, 28, 29, and 30V – TS: 360, 420, and 690mm/min – Heat input: 0.35, 0.43, 0.48, 0.49, 0.54, 0.60, 0.61, 0.66, and 0.75kJ/mm – SGFR: 16l/min
Sathiya et al., [16]	GMAW process	– Super austenitic stainless AISI 904L size 100mm×40mm× 5mm. – Filler wire 1.20mm diameter. – Shielding gas type is Argon	– AV: 28, 30, and 32V – TS: 90, 100, and 110mm/min – WFR: 1.5, 1.75, and 2.0m/min – SGFR: 12, 14, 16l/min – Nozzle to electrode tip distance is kept as 15mm

Authors and year	Welding process type	Materials and consumables	Welding parameters
Sathiya et al., [34]	GMAW process	– Super austenitic stainless steel 904L size 100mm× 40mm× 5mm – Electrode wire 1.2mm diameter. – Shielding gas - Ar	– AV: 28-32V – WFR: 1.5-2m/min – TS: 90-110mm/min – SGFR: 12-16l/min
Sen et al., [36]	GMAW process with double pulsed (DP-GMAW).	– Mild steel plate 0.15% carbon, size 150mm×150mm×9mm – ER80S-G, uncoated welding wire of diameter 1.2mm. – Shielding gas mixture 92% Ar+8% CO_2	– WC: 220, 240, 260, 280, and 300A – AV: 20, 23, 26, 29 and 32V – Thermal pulse frequency: 0.4, 0.6, 0.8, 1.0 and 1.2Hz – Pulse frequency: 70, 120, 170, 220 and 270Hz – CTWD: 18mm – TS: 400mm/min
Singh et al., [45]	GMAW setup FRONIUS TPS 3200 and The travel speed are controlled by mechanized trolley.	– Base material AISI 201LN 150mm×130mm×3mm – Shielding gas mixture of 98% Ar+2% CO_2	– WC: 145, 176, 176A – AV: 17, 17, 18V – TS: 250, 280, 250mm/min – Heat input: 0.59, 0.64, 0.76kJ/mm – SGFR: 18l/min – Root gap: 2mm
Srivastava and Garg [3]	GMAW process with automatic operation	– IS 2062 mild steel plate of 100mm×50mm×6mm – Electrode copper coated mild steel wire, diameter 1.2mm – Shielding gas CO_2	– AV: 24, 28, and 32V – TS: 160, 190, and 220mm/min – SGFR: 10, 14 and18l/min – WFR: 4.5, 7, and 9.5m/min – Torch position-inclined – WC: 150-250A
Tagimalek et al., [33]	Nanoparticles -Electrode gas metal arc welding devices including FP4M machine and MIG 501 wire feed system.	– Heat resistance steel (SUH 310S) dimensions 10mm×30mm×50mm. – Filler wire diameter of 1mm, AWS/ASME ER 309. – Shielding gas CO_2	– AV: 17 – 32V – WFR: 210 – 253cm/min – TS: 200 - 400mm/min
Tham et al., [24]	GMAW process with OTC DAIHEN, DP-400 P30026 articulated robotic arc welder and jig for downhill welding position.	– Carbon steel plates 6mm thick , – Filler wire ER70S-6, 1.2mm diameter – Shieling gas CO_2	– WC: 100 -250A – AV: 18–30V – TS: 15-72cm/min. – SGFR: 15l/min – Constant wire extension: 13mm – Welding torch inclined from the plate: 45° – and from horizon: 15°
Thompson Martinez et al., [11]	Gas metal arc welding process	– Steel 1020 dimension 6.35mm×300mm×40mm. – Wire electrode 1.2mm of diameter – Shielding gas 96% Ar and 4% CO2	– WFR: 4.8, 5.5, 6.5, 7.5 and 8.2m/min – AV: 17, 20, 24.5, 29 and 32V – TS: 6.6, 8, 10, 12 and 13.4mm/s

3 Summary

GMAW has several input variables that affect weld quality characteristics. Controlling these parameters in different conditions is a very challenging task. Different researchers have tried to optimize the input of welding parameters to obtain the desired weld quality characteristics. Moreover, it is challenging to get the optimum combinations of welding parameters for different conditions. This study mainly focuses on summarizing the existing works of literature based on the investigations undertaken by some researchers; the following conclusions are derived regarding the impact of GMAW input parameters on the weld quality characteristics of steels.

- Arc voltage is one of the main factors that influence bead width and bead height. A rise throughout arc voltage leads to a longer arc and larger droplets, resulting in a wider and flatter weld bead. Based upon that slope of a process, an excess arc voltage causes arc instabilities, spatter, undercut, porosity, and degradation subject to the inclination of the process. Low arc voltage produces narrower beads with greater convexity.
- Welding current has the most significant effect and a strong linear positive connection with all bead geometrical characteristics. Thus, too high a welding current at a specified welding speed generates a large amount of heat and raises the depth of fusion. But, too low a welding current will lead to an incomplete penetration which in turn contributes to achieving poor welded joints.
- Increasing the wire feed rate results in increased penetration, bead height, bead width, and HAZ. An excessive rise in wire feed rate causes an excess of the filler material usage and rises the temperature which results in wide weld bead and excessive penetration.
- Travel speed affects the amount of input temperature, which in turn impacts on welded metal metallurgical structure (heat-affected zone). It has an inverse influence on the size of the weld beads (bead height, bead width, and penetration). While the travel speed is fast, the arc forces, arc heat, and droplet impingement are not focused on the molten pool, the downward molten pool will be smaller, the downward flow pattern will be weaker and the amount of molten pool which penetrates the root gap will be smaller. Excessive travel speed results in insufficient penetration due to moving the torch too quickly which doesn't allow enough metal to be deposited in the joint. At a low-level travel speed, the concentration of input temperature rises which leads to higher depth of penetration.
- CTWD is a significant welding parameter that mainly affects the amperage, arc voltage, shielding gas used as well as metal transfer mode. Welding process stability, weld bead profiles, and weld quality are sensitive to CTWD. CTWD has a positive impact on the width of HAZ and the width that occurred into HAZ is stated as the function of CTWD.
- Shielding gas flow rate is one of the welding input parameters that influence the weld bead geometry because the gas flow pressure permits the spreading of material within a state of liquid. The right shielding gas flow rate is important for suitable shielding to the welding region during the heating, liquation, and solidification stages. A lower flow rate of shielding gas revealed useful properties as well as a smaller thermal expansion, greater specific heat capacity, and thermal conductivity than a larger flow rate of shielding gas. The too-low rate of gas flow directed, sourced, and resulted in porous and extra spatter growth/progress owning to insufficient coverage/shielding area of arc. At greater flow rates of shielding gas, coefficients of thermal expansion were greater through a temperature variety range series that directed and resulted in the largest volumetric contraction and expansion inside a weld metal and larger residual stress and HAZ into the structure of the material.
- Work angle variations result in insufficient fusion and undercut, mostly in the vertical material of the fillet weld. Macrostructure, mechanical properties, and microstructure are sensitive to electrode work angle and torch travel angle. When welding with an electrode tilted the size/thickness of the fusion zone reduces according to its motion and the arc penetrates deeper; whereas by the side of an opposite inclination depth of penetration reduces.
- Heat input was primarily a function of arc voltage, current, and travel speed. The amount of heat input determines the radius of the arc, an effective radius of the arc is the most significant variable influencing the establishment of robust geometry on weld bead. Heat input affects the way of molten filler material is transferred, the stability of the

arc, weld bead profile formation, mode of solidification, and metallurgical transformation that disturb the quality and microstructure of the weldment.

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