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Aspects of Multi-pass GTAW of Low Alloyed Steels

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Abstract: Automation of Gas Tungsten-Arc Welding (GTAW) has a high potential for increasing efficiency (increase of arc-time), because manually it is time-consuming and requires high-skilled labour. Moreover it has unique controllability, quality and does not require post-processing. In order to demonstrate the potential, in this paper V-Groove Joints of Low Alloyed Steels are welded together with autonomous, robotized GTAW. Multiple experiments are carried out and analysed in order to establish relationship between robot speed, current, heat input and wire feed. An industrial robot is used for the GTAW process, which is equipped with automatic height-voltage controller and a 3D line scanner. A simple programming interface for welding pass generation and result comparison is also presented.

Keywords: Robotics technology, Intelligent robotics, Information and sensor fusion, Process supervision, Flexible and reconfigurable manufacturing systems.

1. INTRODUCTION

Gas Tungsten-Arc Welding (GTAW), also known as Tungsten Inert Gas (TIG) welding is one of the most difficult and time consuming (compared to other welding procedures) welding type (Egerland et al. (2015); Malhotra et al. (2014)). On the other hand it can produce extremely strong and high quality joints (Handbook (1978); P. P. Thakur and (2016); Takarics et al. (2008)). The method is often used for bicycles, aircrafts, turbines, etc. In addition to GTAW, there are also other welding types, which have attracted researchers and industry. A short overview of these are presented in the following list:

- **Gas Metal Arc Welding** also called Metal Inert Gas (MIG), is an automated welding, which consists of the use of a welding gun which automatically feeds the weld metal through the gun for use. The weld gun also automatically distributes a protective gas (mostly argon based or a mix of argon and carbon dioxide (CO_2)) as a shield from the natural elements. Nowadays it is used extensively in automotive and sheet metal industry Kah et al. (2013).
- **Shielded Metal Arc Welding** (SMAW) also called 'stick welding', one of the most popular and widely used processes in welding today, because it is inexpensive and simple. With using an electrode that has flux around it, it is able to protect the weld puddle from atmospheric contamination Alkahla and Pervaiz (2017).
- **Electroslag Welding** has been in practice since the mid-1950s and particularly suitable for vertical position. Electroslag is a generally fast welding process used to join large materials like thick steel plates (between 25-300 mm) Iyama et al. (2019).
- **Flux Cored Welding** was developed in 20th century, very similar to MIG welding except it uses a special tubular wire filled with flux; it can be used with or without shielding gas, depending on the filler. The method is suitable for wide range of materials and situations. In addition it is very fast to apply Naidu et al. (2003).
- **Laser Beam Welding** is a versatile process, especially suitable for automation. The heat source origins from a laser beam which cause very accurate and high-quality welds, with smaller heat affected zone and higher penetration. This method is mainly applied for large-scale manufacturing due to its high power capability, easy-to-automated feature Auwal et al. (2018a,b); Martukanitz (2005).
- **Cold Metal Tranfer Welding** (CMT) is one of the state-of-the-art technology, which uses much less heat than other welding techniques, thus it is very useful for materials which cannot stand high heat input e.g. aluminum but it can treat steel as well. CMT welding operates with alternating hot and cold treatment, and able to perform very accurate welds Selvi et al. (2018).

GTAW process is based on the electric arc established between a non-consumable electrode of tungsten and the work-pieces to be joined. Part of the heat generated by the electric arc is added to the work-pieces, promoting the formation of a weld pool, the part not transferred to the work piece, is lost through radiation, convection, electrode heating and heat conduction in the TIG torch. Grooves can be filled with filler material, which is fed into and melted at the weld pool. The weld area is protected from atmospheric contamination by an inert shielding gas such as argon or helium. This process is extensively used for stainless steel, aluminium, magnesium and titanium alloys as well

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as pieces of carbon and low alloy steels Stenbacka (2013). In GTAW welding the heat input is mainly depending on three factors: current, voltage and welding speed, and with precise control of these parameters, the exact heat addition can be achieved, which results the production of high quality welds, with low distortion and free of spatter. On the other hand the method is quite expensive, time consuming (e.g. compared to GMAW) and sensitive for environmental affects (e.g. airflow in the welding zone).

Use of GTAW in Wire and arc additive manufacturing (WAAM) can be a promising application. As previously introduced, unlike to e.g. GMAW, GTAW produces spatter free, low distortion welds, which makes GTAW a perfect candidate for WAAM, where the layer-by-layer additive manufacturing requires such properties. Major benefit from WAAM is creating a near net-shape product at the end. The product material properties and overall quality is highly dependent on the welding technology and filler material. While e.g. GMAW produces welds, which need after-process cleaning (grinding of weld seams), GTAW provides a clean finish (spatter free), which allows a continuous (can weld without any process steps between layers) multi-pass welding. However this cleanness comes with a high cost (both in arc-time and operation cost) and this results little interest from industrial usage of autonomous GTAW solutions. In addition, WAAM has been attracting in the last decade many research groups attention Xiong et al. (2013); Ding et al. (2016a); Baranyi et al. (2007); Fang et al. (2017c). In order to manufacture large components, the additive manufacturing outperforms it counterpart - subtractive manufacturing - due to lower waste and cost levels Adam (2016). There were many trials and suggestions on improving the process stability with arc welding based solutions (e.g. GMAW)), however these were focusing on the Computer Aided Design (CAD) to robotized motion planning Ding et al. (2016b); Fang et al. (2017a) and there were only a limited number of studies on the welding process stability itself Kim et al. (2002).

The other use of GTAW can be in welding of voluminous parts. This type of welding typically requires multi-pass welds. Such parts could be e.g. hydro-power water turbines, where sizes range from 1.4 to 14 meters in diameter, combined with weights from 1 to 35 tons. In these cases the welding is required in the connection point for the boss/ring and the blades, where the geometry of welding area could be described as V-Grooves, with changing cross-section geometry and welding passes with many degrees of freedom, as shown in Fig. 1.

Typical solution today to weld the boss/ring and blades together is done by hand, with manual welding techniques (e.g. electrode or MIG/MAG) followed up by grinding along the whole welding seam, after each pass, to remove spatters. The welding sequence is described in the Welding Procedure Specification (WPS) and the amount of passes to fill the V-Groove is depending the expertise and efficiency of the welder.

As it can be seen in both cases (WAAM and V-Groove) the need for accurate planning and closed-loop control of the welding process is necessary. In this paper we put the emphasize on these challenges and propose a generic solution for planning multi-pass welds with GTAW.

Fig. 1. A hydro-power water turbine with the welding grooves

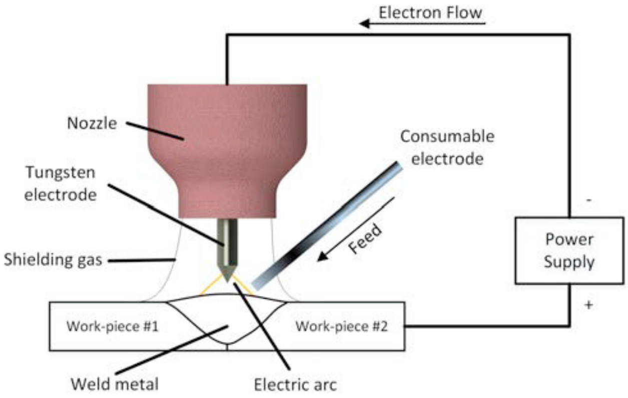


Fig. 2. Overview of welding process with GTAW in Direct Current Electrode Negative (DCEN) setup

The rest of the paper is organized as following: in Sec. 2. the GTAW welding process is introduced, followed by Sec. 3., where multi-pass welding processes and expectations are described. In Sec. 4. the experiments are detailed, while the experiments are discussed in Sec. 5. and the results of the paper is concluded in Sec. 6.

2. GAS TUNGSTEN ARC WELDING (GTAW)

In the process of GTAW a non-consumable electrode is used together with a gas, which is used to shield the weld pool from the oxygen in the atmosphere Tarng et al. (1999). The gas protects the weld pool until the work-piece solidifies, making it far less likely to oxidise. The gas also increases the conductivity between the electrode and work piece, making it possible to strike an electric arc. The electrode is made of tungsten, which has a melting point of $3422°C$, and in our case, the low alloy steel's melting point is $1400°C$. This property of the tungsten enables the electrode to remain solid during the weld, which allows a precise control of the electric arc, and therefore the heat input Kutelu et al. (2018). The method is also known as TIG, tungsten inert gas. An overview picture of the welding process is shown in Fig. 2.

A typical GTAW system consist of a power supply, typically operating between 3 to 500 A, and 10 to 35 V, a welding torch (holding the tungsten and gas nozzle), wire feeder and a gas tank. A GTAW power source can serve both direct and alternating currents, depending on the material- and filler-type. In case of autonomous, robotized GTAW, the power supply is connected to a programmable logic controller (PLC) and the welding process parameters are controlled through the power supply Stadler et al. (2017). The following parameters are adjustable in an autonomous welding setup through the power supply:

- Current $[A]$
- Wire feed rate $[mm/min]$
- Gas flow rate $[l/min]$

While the following parameters are adjusted in the robot system:

- Welding speed $[mm/s]$
- Voltage $[V]$

As it can be seen from this two enumerations above, some of the critical parameters for controlling the welding process are controlled decentralized, and needs careful planning and execution Yang et al. (2017); Tusek (2000).

In the following the main advantages and disadvantages of GTAW are listed:

Advantages:

(1) Makes high quality welds in almost all alloys (e.g. aluminium, stainless steel, Ni 200, copper anode)
(2) Minimal post weld clean up required (compares to e.g. GMAW)
(3) The arc carries no filler, so there is little to none spatter compared to GMAW.
(4) No slag produced that can be trapped in the weld.
(5) Welding can be performed in all positions

Disadvantages:

(1) The GTAW is not a high production or high deposit-rate welding process compared to GMAW
(2) Requires a highly skilled operator (manual GTAW needs two-hand coordination)
(3) Prone to pollution due to unclean work area
(4) Hard to weld in difficult operator positions (e.g. upside down)

3. MULTI-PASS WELDING OF V-GROOVE JOINTS

Manual multi-pass welding, compared to single pass, is more challenging as the planning and execution in many cases are not aligned (WPS only describes guidelines for amount of filling passes). Welders adjust the amount of required filling passes (welds between the root and top) according to the remaining volume, as shown in Fig. 3. Quality, finish of the weld surface is highly depending on the expertise and dedication of the welder. This opens the necessity for autonomous, robotized welding.

On the other hand, autonomous and robotized solution for multi-pass welds require more precise description of the welding sequence, along with exact expectation (e.g. cross-section area) of the resulting geometry after each pass. Yan et al. (2016); Fang et al. (2017b) proposes optimal pass planning for multi-pass welding with GMAW, but only simulation results are achieved and discussed. These approaches provide a generic solution based on Computer Aided Design (CAD) and are able to generate a multi-pass plan, for the given geometry, which will be filled with welding seams. Their approach take into consideration the limitations of the industrial robot and knowledge from WPS, but doesn't learn, neither knows anything from the actual welding process. It helps the welding operators to program an industrial robot off-line (simulated). No details are presented on the user-interface or usability of their solution.

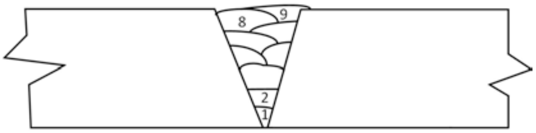


Fig. 3. Extract from a multi-pass WPS. The numbers refer to a specific welding procedure (parameters), exact amount of fill passes are not specified, only shown in the plan

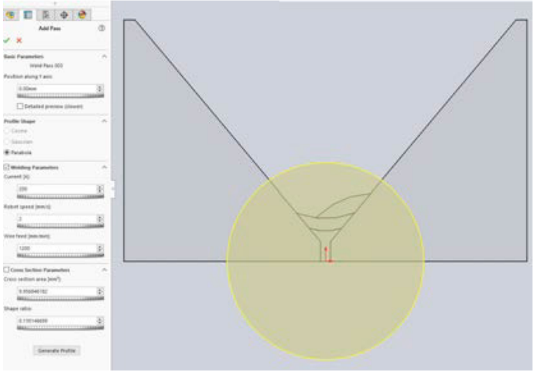
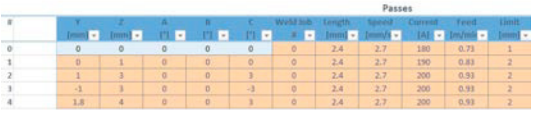


Fig. 4. CAD based planning of passes



Passes

#	Y [mm]	Z [mm]	A [°]	B [°]	C [°]	Weld Job #	Length [mm]	Speed [mm/s]	Current [A]	Feed [m/min]	Limit [mm]
0	0	0	0	0	0	0	2.4	2.7	180	0.73	1
1	0	1	0	0	0	0	2.4	2.7	190	0.83	2
2	1	3	0	0	3	0	2.4	2.7	200	0.93	2
3	-1	3	0	0	-3	0	2.4	2.7	200	0.93	2
4	1.8	4	0	0	3	0	2.4	2.7	200	0.93	2

Fig. 5. Excel spreadsheet based planning of passes

In this paper, the opposite approach is demonstrated: the welding operator needs to define the expected passes for the welds in a CAD (see Fig. 4) or simple Excel spreadsheet (see Fig. 5), and the industrial robot executes the welding according to this. The complexity of robot controller, calibration, programming is hidden from the welding operator. Currently this approach is limited to straight line welds, but expansion to arbitrary directions is ongoing. As it will be also described in the Sec. 4, the goal was to create a robust environment, which eliminates the uncertainties of the welding process itself.

The pass planning is based on WPS and the welding operator needs to specify, where the exact location of the welding seam should be. This can be done in CAD environment as shown in Fig. 4. Beside the horizontal position, the operator needs to specify the requested welding parameters: current, voltage, welding speed, feed rate of the wire. The vertical position of the weld is automatically calculated the following way:

(1) Based on the welding parameters, an expected cross-section area is calculated (given in mm^2), this calculation is based on measured previous welding infor-

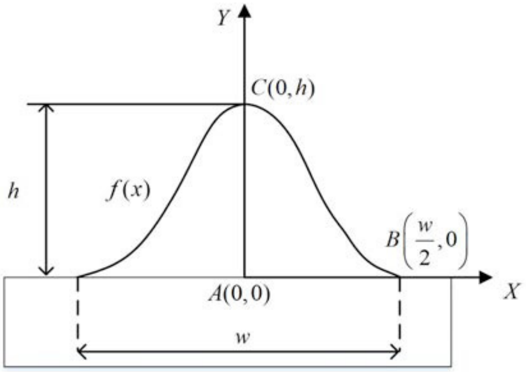


Fig. 6. Parabola profile shape weld seam representation. w is representing the width, h is representing the height

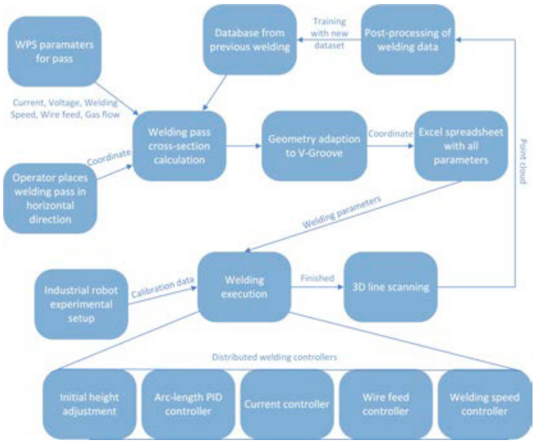


Fig. 7.

mation, which is captured at the end of the process by using 3D line scanner to record the surface of the pass

(2) Based on the given horizontal position (mm, relative from the root position), a parabola profile shape is sketched (as shown in Fig.6). The area of the parabola is equal to the cross-section area, which was calculated in point (1)
(3) In multiple iterations the parabola shape's (width and height) is adjusted to match the underlying geometries

The operator builds up the welding passes from pass to pass and at a final stage it exports the results to an Excel spreadsheet (as shown in Fig. 5), which can be directly used in the experimental welding system. When the planning is finished, path planning for the robotized execution of the GTAW weld is carried out automatically in an off-line programming tool and the resulting robot motion program with the corresponding welding parameters are transferred to the robot automatically. The process is demonstrated in Fig. 7.

The experimental setup for this is shown in Fig. 8. The experimental setup composes from the following elements:

- KUKA KR30 industrial robot equipped with a GTAW welding torch
- Welding power supply
- Shielding gas tank and supply

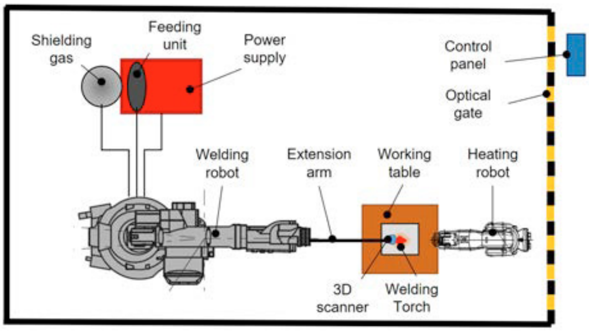


Fig. 8. Experimental setup

- Heating industrial robot, for the purpose of preheating the material according to the WPS (not part of the multi-pass planning)
- Work-table

The setup is similar to an industrial environment (including pre- and post-heating) and allows repetitive testing of the welding processes.

4. EXPERIMENTS

In order to evaluate the robustness of the welding process, six V-Groove Joints were welded. Robustness of the process is measured in how good the actual welding plan is matching the finished welding geometries. This is measured with use of a 3D line scanner after each pass of welding. All V-Groove profiles have 25 mm height and 35 ° or 40 ° angle, each contained more than 30 welding passes to be filled. Due to page limitations it is not possible to disclose all the 219 passes welding parameters in detail. All welding was executed with 12 V on the same base material (*304L steel*) and with same filler material (*Böhler 13/4-IG*). A summarizing table about the experimental workpieces can be seen on Table 1.

The tests were repetitive (Work piece 1-4, 5-6 were identical), therefore basically used the same welding parameters – small differences occurred in order to optimise the welding– which are suggested by the WPS. Despite of this, small deviations were observable both in the area of the beads (thus the required number of passes) and the quality of welds.

After each welding pass a 3D line scanner was used in order to investigate and measure the weld bead. As Fig. 9 shows scanning works well an precisely. Although in multi-pass cases the height and width of the bead is not so deterministic, mainly due to the uneven surface and the edge of the groove, thus only the area was used. Each bead was measured at least two different places and the average were taken to decrease uncertainties (Morioka et al. (2010)).

The finished work pieces were cut in two parts and microscopic images were taken. In some cases root pass cracks and small impurities in the weld area were observable Fig. 10.

Table 1. Main characteristics of multi-pass welding experiments in straight V-Grooves

Work piece	Current range [A]	Speed range $[\frac{mm}{sec}]$	Feed range $[\frac{mm}{min}]$	Heat Input Range $[\frac{kJ}{mm}]$	Profile Angle [°]	Number of passes	Range of Cross Section Area $[mm^2]$
1	160-260	2,2-4	500-1500	0,32-0,81	35	38	3,9-12,9
2	180-260	2,2-3,5	600-1800	0,37-0,79	35	36	6,12-14,75
3	200-250	2,25-3	750-2050	0,48-0,78	35	35	1-14,82
4	200-250	2,25-3	750-2050	0,48-0,78	35	35	5,08-14,52
5	180-240	2,25-2,7	730-1600	0,48-0,76	40	40	4-13,47
6	180-240	2,25-2,7	730-1800	0,48-0,76	40	35	3,75-14,08

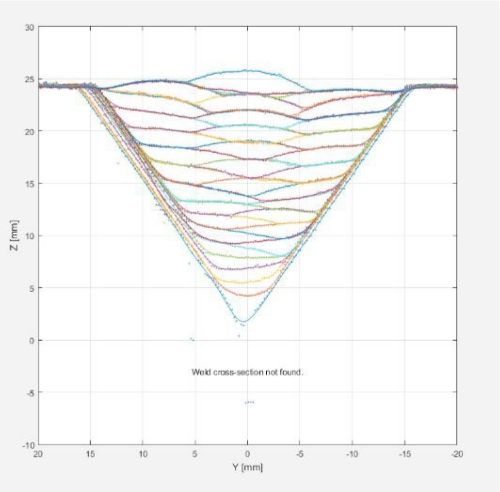


Fig. 9. Measured values of a weld bead

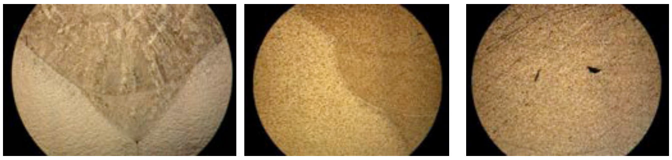


Fig. 10. Macroscopic images of multi-pass welding from work piece Nr 1. (cross-section)

5. EXPERIMENTAL RESULTS

During the execution of the experiments all welding parameters were continuously recorded (approx. every 2ms). Based on the welding test described in Sec. 4, the parameters that influence the cross-section and the appearance of the weld, are the following:

- Voltage (U) $[V]$
- Current (I) $[A]$
- Robot (welding) speed (v) $[mm/sec]$
- Feed of the wire (f) $[mm/min]$
- Deposition rate $\xi \cdot {D_{wire}}^2 \cdot f$, where D $[mm]$ is the diameter of the filler wire

The relations of the voltage, current and robot speed is defined in the heat input (Q):

$$Q = \eta \cdot \frac{U \cdot I}{v}$$

η – arc efficiency, for GTAW welding and 304L steel: $\eta = 0.6$ (Stenbacka (2013)).

Each of the parameters influence the weld differently:

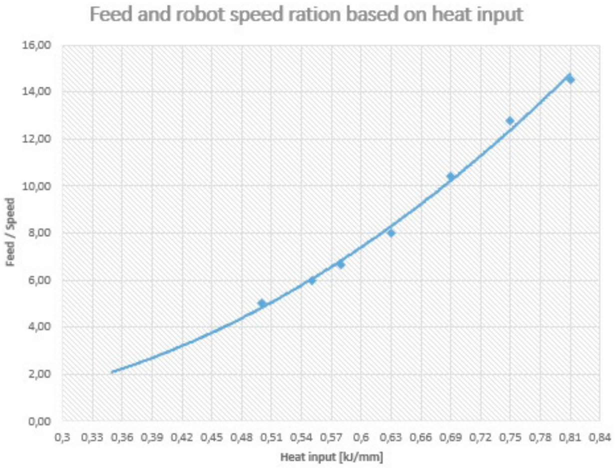


Fig. 11. Relation between heat input, feed and robot speed

- Voltage: by increasing the voltage, the bead of the weld is wider. It does not influence the penetration.
- Current: by increasing the current, the penetration is increased and so is the width of the weld. Thus, higher current – wider and flatter the weld.
- Robot speed and wire feed: these two parameters by themselves do not influence the appearance of the weld. It is the ratio of these two that is important. Speed needs to be low enough to allow the arc to melt the wire that is being fed to the weld pool.

Based on the above described influences of mentioned parameters, the relation between heat input and ratio of robot speed and wire feed was investigated. The voltage is being kept constant during all the tests and the following explanations. Based on the data from the six multi-pass work piece welding tests (using parameters v, f, Q), the following graph was obtained (Fig. 11).

By increasing the heat input, more wire is being fed into the weld pool. This provides the welds with larger cross section area. At the low values of heat input, either the current is small or the speed is high, so the wire feed needs to lower as well. As the current increases, or the speed decreases, more wire can be fed, thus the ratio of the feed/speed increases on the graph.

However, since the heat input can be kept constant by increasing the current and increasing the robot speed, at the same time, this graph does not provide the satisfactory data. By doing that, the feed needs to be increased as well, in order to keep the ratio feed/speed constant. In this case: for the same heat input, two different set of parameters are used (current, speed, feed) which produce welds of different cross area.

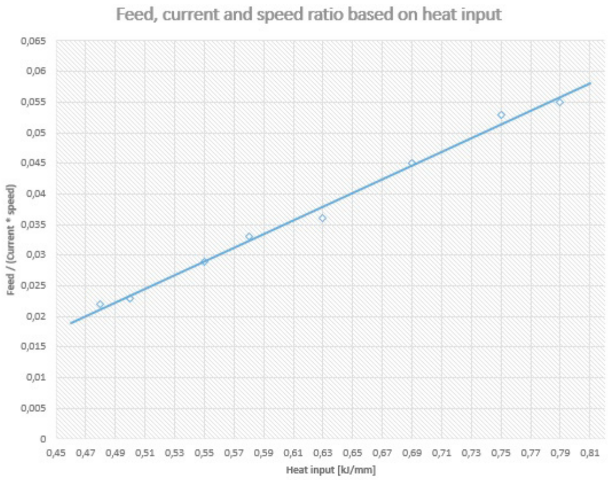


Fig. 12. Relation between heat input, feed, current and robot speed

Since the value of the current has significant influence over the weld appearance and the cross section area, it was attempted to find a relation of the parameters that would obtain all the necessary information to provide a good weld with maximum deposition for the given heat input (Fig. 12). This was tried with the relation: $f/(I * v)$ $[A/s]$.

The line represents the maximum feed for the given heat input and current. In theory, if the feed-current-speed ratio is on the line, the weld will be good with large cross section area. If the ratio of these parameters are over the line, the weld will be beaded, and if they are below the line, weld will be flat with small cross section area. This observation is based on the recorded data.

6. CONCLUSION

In this paper welding of V-Groove Joints were investigated with autonomous, robotized GTAW. As shown here, today's solution with manual welding can be replaced with intelligent planning tool and robotized system. An experimental setup with 6 experiments were presented. Through analysis of the results: the precise control of welding parameters is the key for successful application. The inter-dependency between robot speed, welding current, feed rate and heat input was shown.

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