Local reinforcement of titanium sheet by means of GTAW droplet deposition for threaded connections

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Abstract. Making threaded connections to thin metal sheets requires locally thickening of the sheet in order to provide enough thread length for a structurally sound connection. Shaped Metal Deposition processes like Gas Tungsten Arc Welding (GTAW) allow to locally build-up material in order to provide thickness for a sufficient length of thread engagement. This publication describes the research towards local thickening of a titanium sheet by means of pulsed Tungsten Inert Gas (TIG) droplet deposition, aimed at creating threaded holes for thin shelled bone fracture fixation plates. The influence of current, weld time and amount of filler material on droplet diameter and height is studied.

Introduction

The introduction of Incremental Sheet Forming processes allows for a cost-effective access to customized sheet metal products. Although these processes excel at creating a wide variety of shell geometries without the need for extensive machine or tooling requirements, they are not able to provide local thickening of the sheet for structural purposes. Merklein et. al.[1] provided a useful overview of ways to obtain thickness variations of the blank prior to forming through the use of tailored welded or rolled blanks or patchwork blanks (by attaching a secondary sheet layer). The succeeding forming step however often induces excessive stressing of the interface between patch and sheet or at the circumference of the thickened zone leading to delamination or fracture. Ambrogio et. al. [2] demonstrated the potential of using selective laser sintering prior to incremental forming for increasing the dimensional accuracy, thickness distribution and achievable shape complexity of a stainless steel part. Bambach et al. [3] have discussed the use of Laser Metal Deposition (LMD) on a pre-formed cup made of EN AW 6082, to increase its stiffness with only limited weight increase. LMD allows for a wide geometry variation both of the substrate and added volume. A review on hybrid process chains, combining sheet forming and additive manufacturing (AM) was published by Hafenecker et.al. [4]. They acknowledge the potential for stiffness control and the possible synergy of combining AM prior to forming and vice versa. However they also identified the lack of knowledge on how material flow is altered by the additive structures, the changes in material properties as a function of the selected process sequence and thermal distortions of formed parts and changing residual stresses due to AM processes.

The requirements for thickening of metal sheets for threaded connections are less complex. In contrast to cladding entire areas or building up stiffening ribs, threaded connections often only need a very limited area of increased thickness around the hole and are typically performed after the forming operation of the part.

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The application envisaged in this article consists of threaded connections to accommodate osteosynthesis locking screws in thin walled medical fracture fixation plates [5]. These plates, with a thickness of 0.5-1.5mm, especially require local bulking of the sheet in order to provide enough thread length for the head of the locking screw [6] Fig 1(a). Popular means of providing thread length are attaching a pre-made threaded fastener, such as a rivet nut, clinch nut, weld nut or cage nut [7]. These processes, however, require a foreign body to be connected to the sheet and are thus less suitable for medical applications. Friction drilling and tapping of the created bushing has been studied as a process to create threaded holes without addition of external material, but it is challenging to perform in titanium due to its low thermal conductivity [6, 7] Fig1(b).

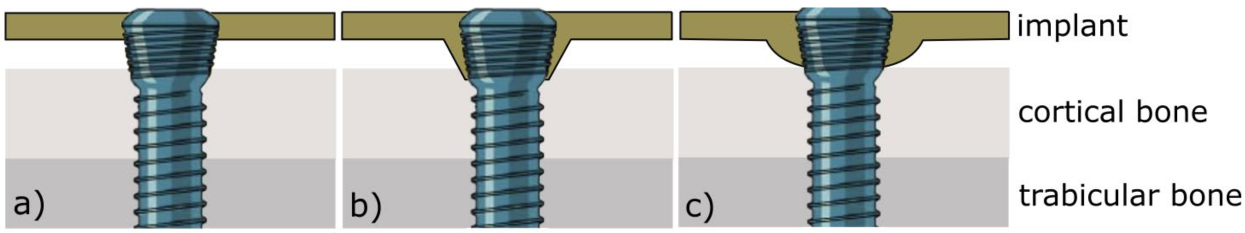

Figure 1. Medical implant fixation through locking screws (based on)[8]: (a) implant with insufficient thread length, (b) thickening through friction drilling, (c) thickening through droplet deposition

The use of additive manufacturing techniques to deposit single droplets on pre-formed titanium implants, enables sufficient adhesion and thread length whilst thermal deformation is kept to a minimum. Given the pre-shaped freeform geometry of the substrate, metal deposition techniques are advisable. This publication describes the use of Shaped Metal Deposition (SMD) techniques using Gas Tungsten Arc Welding (GTAW) with wire feedstock for droplet deposition. As one of the Wire Arc Additive Manufacturing (WAAM) techniques, it finds its roots in the 1920s patent by Baker [9]. It has the benefit of a stable arc, high deposition rates, low splashing, reduced material waste and limited cost. The main disadvantage is the low deposition resolution. [10]. The major process parameters identified to influence the deposited geometry are: volume of infeed material (diameter of wire x wire speed), welding current and welding speed [11-12]. Most studies have been performed on single or multiple beads. Analysis on the deposition in single spots is lacking.

This paper will investigate the influence of current, wire amount and welding time on the diameter and height of a single spot for GTAW additive manufacturing of Titanium Grade 2.

Material and methods

The workpiece material selected is Titanium grade 2 with a thickness of 1mm. This grade is extensively employed in medical applications owing to its superior strength-to-weight ratio, biocompatibility, absence of magnetic attraction, and widespread accessibility.

The thermal conductivity of titanium is notably lower than that of steel, conveying both advantages and disadvantages to the welding process. The required heat for welding becomes more concentrated and dissipates less to the surrounding base material. However, the reduced conductivity results in a pronounced gradient in material properties. The low coefficient of thermal expansion in titanium reduces thermal stresses following the welding process [13].

Table 1. Properties of Titanium Grade 2.

Density [Kg/m³]	4510
Youngs modulus [GPa]	100 - 105
Yield strength [MPa]	276 - 400
Hardness, Vickers [HV]	145 - 165
Thermal Conductivity [W/(mK)]	16 - 18
Melting Point [°C]	1670

An unalloyed filler wire material ERTI-1 of 1.6mm diameter is chosen for its ductility and lower yield strength, enabling a better forming or cutting of thread for the locking screw fixation

Table 2. Chemical composition of Ti2 and filler material ERTi-1

	wt % C	wt % N	wt % Fe	wt % O	wt % H
Ti 2	0,08	0,03	0,030	0,025	0,015
ERTi-1	0,03	0,012	0,08	0,03 - 0,10	0,005

Titanium becomes highly reactive with oxygen, hydrogen, and nitrogen when exposed to temperatures above 500 °C. These elements can be absorbed, migrating to interstitial sites and causing brittleness. To prevent this embrittlement, the use of shielding and backing gas during the welding process with titanium is required. The titanium must be protected until it cools below 260°C. The weld is shielded by a 8 l/min pure argon flow supplied through the TIG torch with a mounted gas lens to ensure a laminar flow (Fig 2.).

The back of the sheet is protected with the same argon as backing gas, flowing at a rate of 1l/min in a chamber at the backside of the sheet (Fig 2)

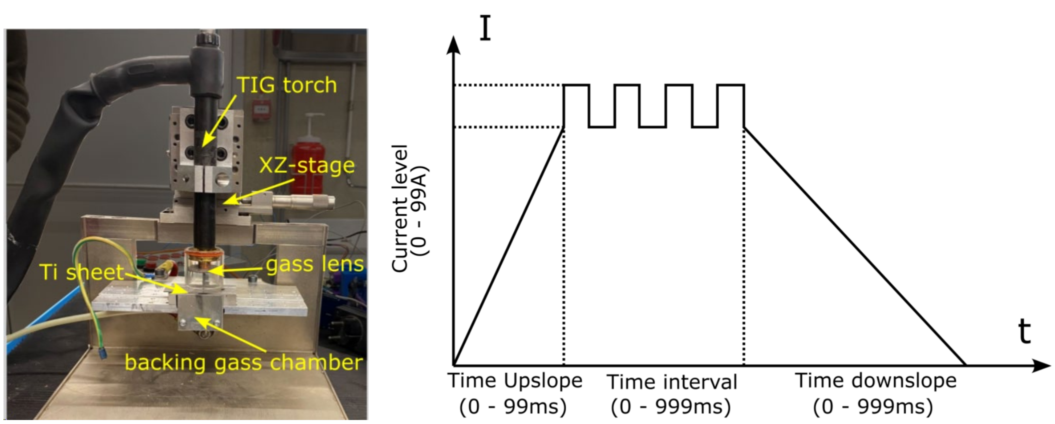

Figure 2. a) Picture of TIG welding platform and b) schematic of Tig source current profile

A pulsed arc power supply from MacGregor was used as power source which is able to generate an arc for a time interval of 0-999ms second, preceded and followed by a respective programmable upslope (0-99ms) and downslope(0-999ms) with a resolution of 1ms. The current can be set between 0 and 99A in steps of 0.1A. The arc current has the option for a pulsed profile. (Fig 2b).

A purpose built feeder system, which is synchronized with the source, enables a controlled amount of filler material during the arc duration. The filler wire is fed into the arc through a guiding system parallel to the workpiece and retracted before the downslope is started (Fig 3.);.

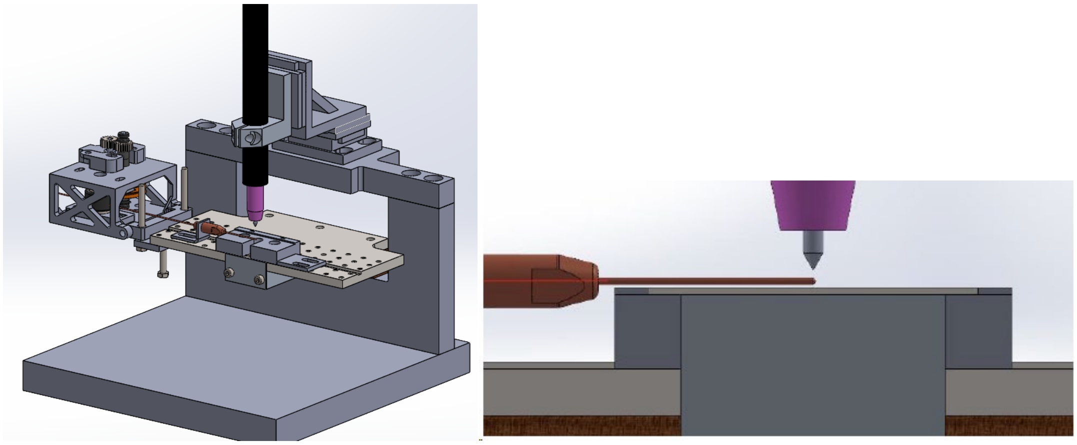

Figure 3. Design of the feeder system for filler wire

The stand-off distance of the tungsten electrode and the workpiece was kept constant at 3mm by means of the XZ stage. The electrode was ground to a 30° tip angle.
The droplet dimensions are measured by slicing the droplet through the center using EDM and measuring the diameter by optically choosing the intersection between the blank sheet and the start of the thickened zone and the height as the length between the original blank sheet end the top of the thickened zone (Fig 4). The measurements were repeated 3 times.

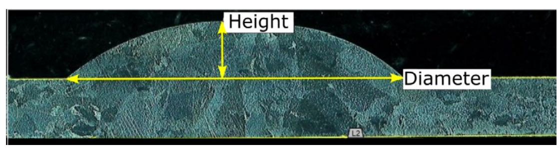

Figure 4. Overview of droplet dimensions

This study focusses on the influence of the welding current (I), welding time (t_w) and length of wire fed into the arc (L_w) on the height and the diameter of the droplet through a factorial analysis. Minitab 18 was used to perform the factorial analysis. The investigated variables and their ranges are presented in Table 3, accompanied by a summary of the fixed parameters. Every parameter set is executed six times in random order. Between two tests the sheets are verified to be below 30°C.

Table 3. Overview of process parameters

Variables	low	high
Current (I)	60 A	99 A
Weld time (t_w)	600 ms	999 ms
Length of filler wire (L_w)	0 mm	6 mm

Fixed parameters			
Upslope time	99 ms	Argon flow rate torch	8 l/min
Downslope	999 ms	Argon flow rate backing	1 l/min
Filler wire diameter	1,6 mm	Temperature baseplate	<30°C
Stand-off distance	3 mm	Plate thickness	1 mm
Base material	Ti-2	Filler material	ERTi-1
Electrode angle	30°		

Results and discussion

Droplet Diameter: The analysis results showed a significant influence of current and weld time as single factor on the droplet diameter (Fig 5). It can be seen that the diameter increase significantly when the current or the weld time increases, with the current having the highest effect. An increase in current will provide a higher heat flux to the melt, which becomes less viscous and can thus spread to a wider diameter. A longer weld time allows the heated or molten zone to spread to a larger diameter. The wire length did not have a significant influence on the droplet diameter.

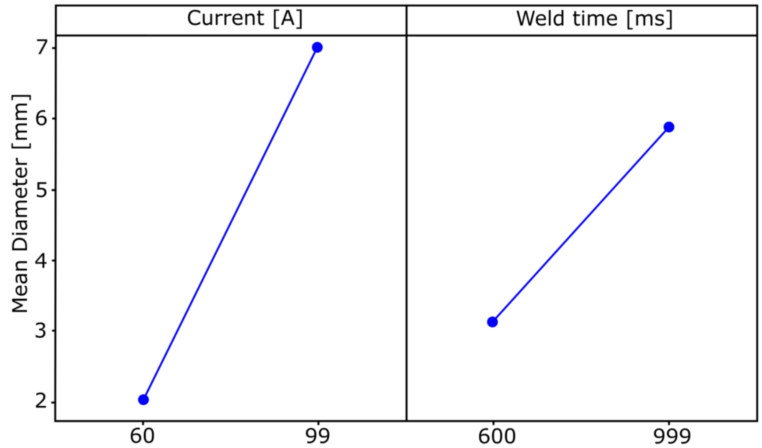

Figure 5. Minitab main effect plots for the weld diameter

The interactions current/weld time and current/wire amount also show a significant effect on the diameter. From the current x weld time interaction it is clear that the diameter is more sensitive to the current when the weld time is short. A high weld time and high current yield the largest diameter. The current x wire length interaction is less sensitive, where no wire input shows a slightly higher effect than the 6mm input.

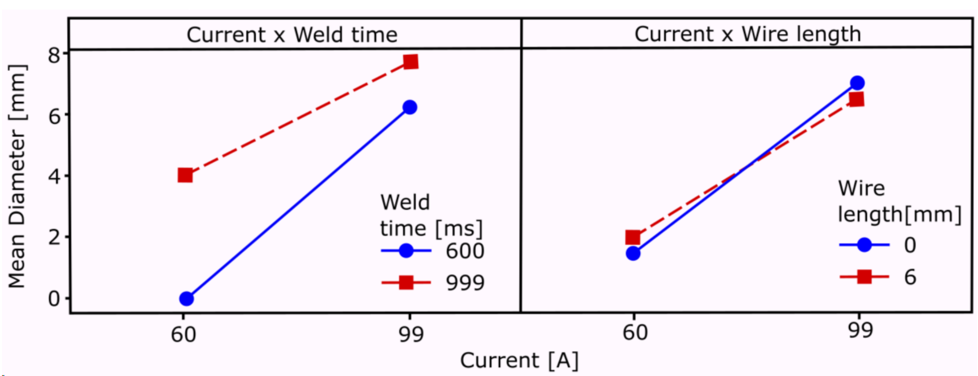

Figure 6. Minitab interaction plot for the diameter

Droplet height: all three variables have a significant influence on the droplet height. The weld time stands out as the major contributing factor. While an increase of the weld time interval or wire length lead to a raised the droplet height, the current has the reverse effect. This can be explained by the fact that a longer weld time will allow a larger volume to melt and thus be attracted towards the center of the droplet. This also clarifies why even without wire infeed there is a significant droplet formed after welding. Furthermore, an increased wire infeed means more material to build up a higher droplet. Finally a higher current will raise the melt temperature and lower the viscosity allowing the melt to spread out more.

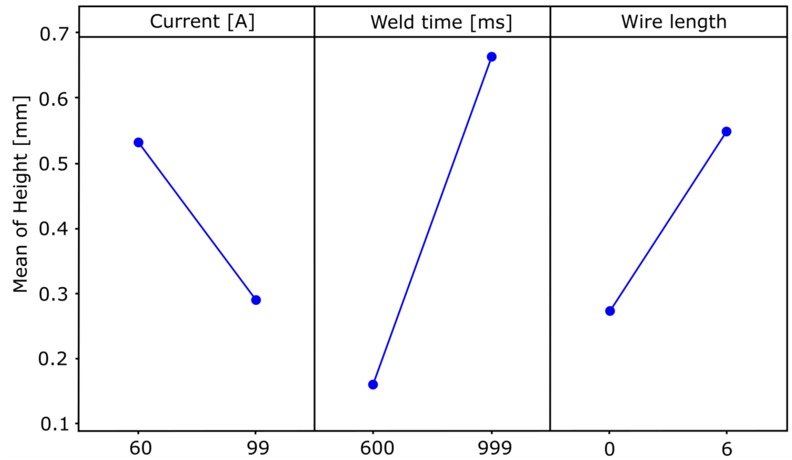

Figure 7. Minitab main effect plots for the weld height

The current x weld time interaction is notably more significant than the others. At a low time interval a raised current leads to an increased droplet height while this relation reverses at a high time interval. This leads to believe that the low weld time is insufficient for the droplet to spread wide before solidification.

Finally, it can be concluded from the weld time x wire length interaction plot, that an increase in weld time has a higher influence on the droplet height when the wire feed is higher.

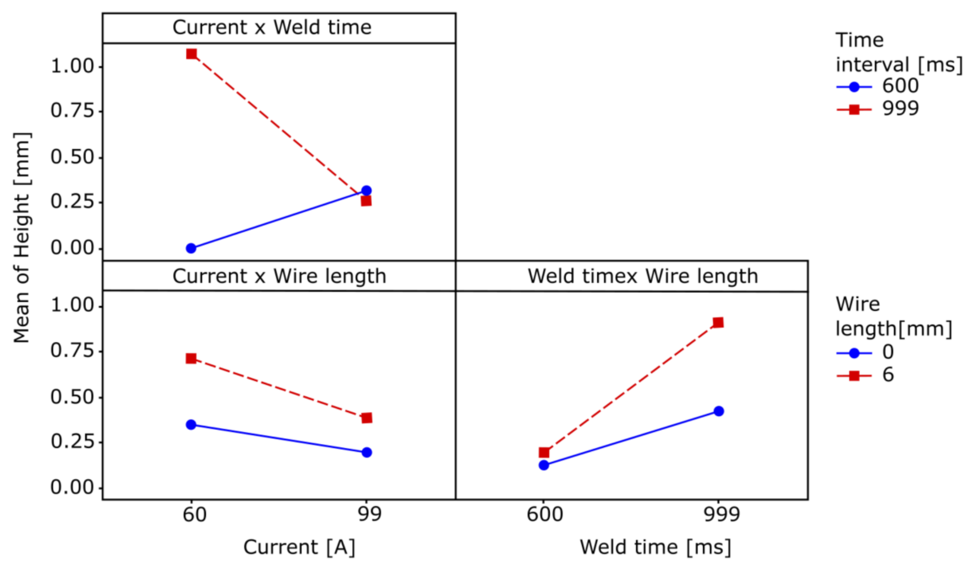

Figure 8. Minitab interaction plot for the weld height

Response surface optimization: For a the implants envisioned as application for this research a droplet height of 0.55mm is set forward to achieve the required thread length. A droplet diameter of 5.5mm suffices for cutting or forming the treads for commercial locking screws while still small enough to limit thermal deformation of the sheet.

Applying Minitab's response optimizer tool to achieve the target values for droplet height and diameter yields the following variable values: a current of 86.5A, weld time of 834ms, and a wire amount of 6mm. The results of the optimizer are depicted in Figure 8

Note that the optimal variable value for wire feed is 6mm which is the maximum tested, which means extra experiments with higher feed length are necessary but were not possible at the time of testing.

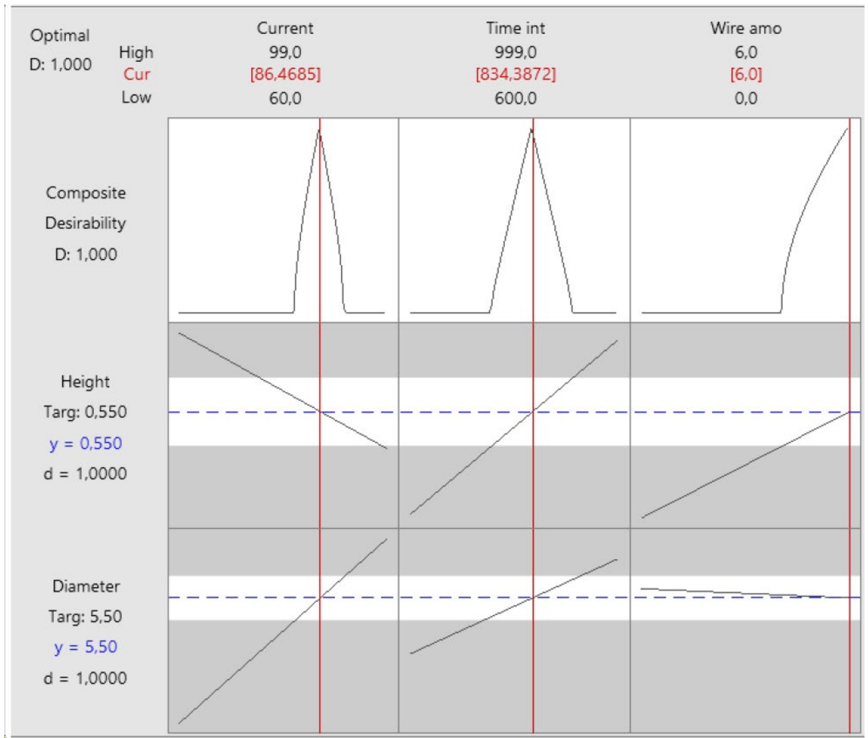

Figure 8. Results optimizer tool for a droplet diameter of 5.5mm and height of 0.5mm

Conclusion and future work

In this paper the influence of current, weld time and amount of wire feed on the diameter and height of the resulting droplet were studied for Ti grade 2.

- While a raised current from 60 to 99A resulted in an extended droplet diameter (2 to 7mm) due to the increased melt pool temperature it showed an inverse correlation to the height (0.54 to 0.39mm) for similar reason.
- An increased weld time (600 to 999ms) lead to both an increased droplet diameter (3 to 6mm) and height (0.16 to 0.67 mm)
- The amount of filler material added only has a significant and positive effect on the droplet height

Future work encompasses the extension to wire lengths exceeding 6mm, drilling the holes for thread and cutting/forming the thread. Finally the mechanical strength of the threaded connection will be tested and accompanying microstructural analysis will be performed.

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