SEVEN
publicações acadêmicas

Welding and additive manufacturing of titanium and its alloys by the gmaw process – Arc instability characteristics

Crossref doi
https://doi.org/10.56238/uniknowindevolp-080

Oksana Kovalenko
Doctor in Mechanical Engineering from the Federal University of Uberlândia
E-mail: okskovalenko@ukr.net

ABSTRACT
The GMAW welding process faces significant challenges when applied in the welding and deposition of titanium and its alloys. Challenges include electric arc instability, unstable metal transfer, splash generation, and the formation of irregular weld beads. Given the existing difficulties there is a constant effort of science to understand and solve them, especially in the context of Arc and Wire Additive Manufacturing, where the GMAW process is highly advantageous due to its high productivity. This work aims to present the evolution of knowledge related to the operational difficulties faced when using the GMAW process for welding and deposition of titanium and its alloys, in addition to highlighting the techniques developed to overcome these challenges. The scientific literature indicates that operational difficulties have their origin in the cathodic emission process. GMAW process applied to titanium is characterized by the emergence of a high-luminosity jet that protrudes frontally. This jet originates from a cathode point, which often changes position, resulting in the formation of irregular weld beads. The phenomenon also makes it difficult to fully incorporate the metal drop into the melting pool, leading to the generation of splashes. Although there are reports that this jet is formed due to thermionic cathodic emission, there are hypotheses of other reasons.

Keywords: Additive Manufacturing, Titanium, Operational Challenges, Arc Instability.

1 INTRODUCTION

Titanium and its alloys began to be used in the welding area from the sixth decade of the twentieth century after having gone through several stages of improvement of the manufacturing process. Initially the most used welding process was GTAW (SALTER and SCOTT, 1967), but with the application of titanium in the nautical and underwater area, which presumes the union of large thicknesses, the need arose to use the GMAW process (STARK, 1966; MITCHELL and FEIGE, 1967). In the literature, reports of operational problems such as unstable arc, unstable metal transfer, generation of splashes and the formation of irregular cords have been observed several times. Although these problems are already known in more common materials, they are more evident and more harmful in the case of titanium. The review presented in this work, for the most part, is dedicated to revealing the information about arc instability during application of GMAW process to titanium and its alloys.

2 REVISION

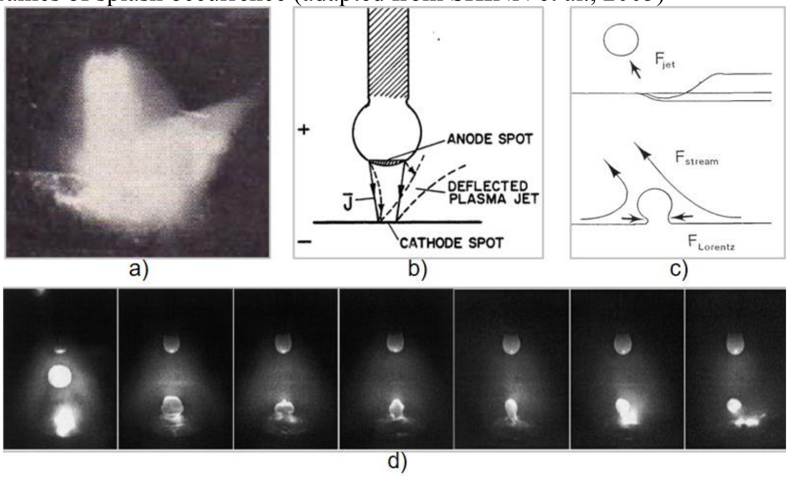
According to the literature, arc instability happens when the GMAW process operates in reverse polarity with low constant current (short-circuit and globular metallic transfer level). Franco-Ferreira and Patriarca (1959) were in these conditions and managed to reduce the arc instability and weld bead irregularity to a minimum, by increasing the current to the level of metal transfer by spray and adjustment of the DBCP, which must be high enough to promote electrode-free extension heating by Joule effect, thus reducing splash generation, but not excessively high, to provoke arc instability. Stark et al. (1962) also stressed the importance of maintaining power at a sufficient level, thus ensuring metal transfer by spray and arc stability, since low power causes arc instability and splash generation. Similarly, Wolfe et al. (1965) declared satisfactory results using spray metal transfer. Regarding short-circuit transfer, Wolfe et al. (1965) reported the slower and longer detachment of drops than with carbon steel or stainless steel. They hypothesized that this may be caused by titanium's high electrical resistivity and recommended increasing the open arc time to maximize the fluidity of the liquid metal, even as using 25% He in the mixture with Ar, but not more, since higher content favors erratic arc behavior and splash generation. From the technical data of titanium it is known that it has the highest melting temperature than steels, leaving to imagine the need for higher levels of current, but at the same time has low levels of conductivity and heat capacity and high level of electrical resistivity, which makes the material require lower current level to maintain the fusion than steels, including stainless ones (AKULOV, 1971).

Salter and Scott (1967) performed the high-speed filming to characterize the behavior of the arc in the conditions of reverse and direct polarity with metallic transfer by short circuit, spray and pulsed. According to their observations, in the reverse polarity arises a cathode jet from the root of the arc in the melting pool, which under a low current dominates the anode jet, making the metal transfer slow and large droplets, which entering the melting pool break into small parts and are projected out of the melting pool, forming the splashes (Figure 1(a)). Already under a larger current, the anode jet strengthens and dominates the cathode jet, apparently because of the formation of several cathode points scattered throughout the fusion pool, increasing the frequency of detachment of the drops and reducing their size. In direct polarity, authors declared, the presence of only one jet of the anode, very unstable, which under a low current slowly rotates around wire-electrode, projecting the drops in the direction of the turn, and with a high current rotates rapidly and the drops divide and turn into various splashes. In negative polarity with pulsed current the arc also remains highly unstable. Already, the pulsed current in the reverse polarity resulted in a regular transfer with a condition of one drop after each pulse, directed to the fusion pool, creating stable conditions of titanium welding. In this condition the cathode jet was also seen, but the detrimental effect for metal transfer was not noticed. The authors also reported that metal transfer is more advantageous with protection in Air +25% He compared to 100% Ar, while protection of 100% He considerably reduces arc deviation, which disagrees with Wolfe et al. (1965).

Ries (1983) in his work obtained results similar to those of Salter and Scott (1967). Among them are the stabilizing effect of the level increase of the constant current and the pulsed current, both in reverse polarity. Direct polarity resulted in a high level of irregularity of metal transfer and cord formation, even with high constant current and pulsed current. According to Reis (1983) a strong cathode jet forms in the fusion pool, enters into interrelationship with anodic jet of lesser force, resulting in the imbalance of forces between the two, affecting the metallic transfer that acts in the opposite direction to the detachment of the drop, partially repels the drops entering the fusion pool, generating the splashes, is wandering, rotating and creating the plasma jet bypass of the electrode axis (Figure 1(b)). The author cites, that the diffuse cathode point (composed of several small points) delivers a more advantageous condition for the arc. In aluminum welding, oxides float on the surface of the melting pool and the molten droplet, serving as more efficient electron emitters than liquid metal. In the case of titanium it is difficult to create a diffuse cathode point, because the oxides dissolve in the molten metal, and the rupture of a stable cathode or anode point in the various small ones is impossible due to insufficient motive force.

Eickhoff and Eagar (1990) defined three forces that participate in the splash generation mechanism (Figure 1(c)), the Lorentz force and the plasma flow force (*stream* force), which are responsible for the separation of a droplet part, which is in transfer to the puddle, and the cathode jet force, which repels that part of the drop out of the puddle. The authors state that titanium is sufficiently refractory and sustains thermionic emission, responsible for concentrated cathode point and presence of a cathode jet. In aluminum, the emission per field can be observed during welding, which is manifested by numerous moving cathode points, without a cathode jet formed. For future work, these authors recommend investigating methods of rupture of the cathode point concentrated in the diffuse, of several cathode points, which will help to avoid splashes. Authors also point out that the presence of a small amount of oxygen in the shielding gas has an equal stabilizing function promoted by the presence of oxides on the surface. It is worth mentioning that the opinion about titanium being the hot cathode, based on this work was found in several other works (SHINN et al., 2005; SEQUEIRA ALMEIDA, 2012; Pardal et al., 2019; CHOUDHURY, MARYA, AMIRTHALINGAM, 2021).

FIGURE 1 – a) Appearance of reverse polarity arc, low constant current (SALTER and SCOTT, 1967); b) Schematization of plasma jet deflection (RIES, 1983); (c) the forces participating in the splash mechanism (EICKHOFF; EAGAR, 1990); d) High-speed filming frames of splash occurrence (adapted from SHINN et al., 2005)



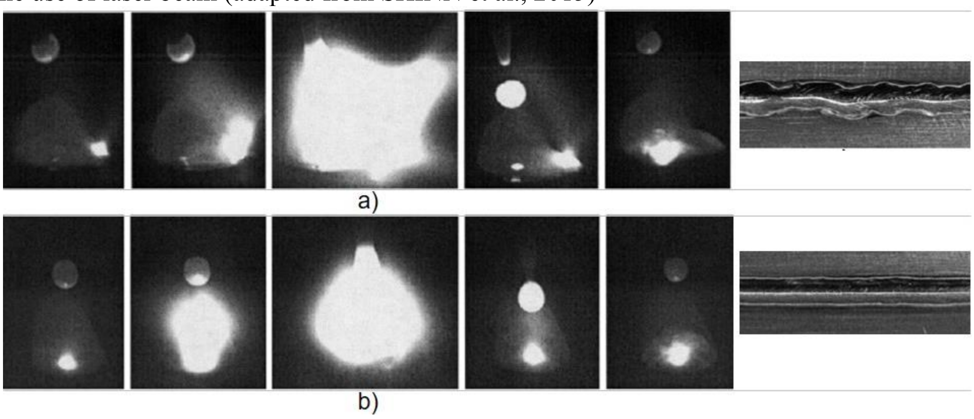
Nishikawa et al. (2000) carried out work with the intention of promoting arc stability by adding a small amount of oxidizing gases in argon in content of 1-5 % of O2 and 2-10 % of CO2 during the welding of Grade 1 titanium by the GMAW process with pulsed current of trapezoidal wave (30 Hz) and square (77 Hz). The results were evaluated from the high-speed filming, cord appearance and mechanical properties. Authors state that arc instability and cord irregularity occur in the case of use of pure air, assuming that this happens because cathode point does not form in a stable way, promoting the spreading of the cathodic cleaning zone and cathode point *wandering* in search of metal oxides, especially when the current level is low. Authors state that the addition of oxidizing gases promotes arc stabilization and cord regularity, but also increases the number of drops per pulse.

Zhang and Li (2001) developed a pulsed current curve, which increases the control of metal transfer, namely, a robust UGPP condition without the generation of splashes, aiming to overcome obstacles present in titanium welding with GMAW process. Authors created the curve that consists of two pulse phases and a base phase between them. The first pulse performs the function of droplet formation, the base current serves to create an oscillation of the droplet and the second pulse serves to proceed the detachment of the drop. They achieved a controlled, robust and repetitive transfer, without deviations of the drops and splash formation. The technology developed is based on the phenomenon of alteration of direction of axial component of the Lorentz electromagnetic force. In relation to values, they showed that for wire of 0.9 mm in diameter the current from 140 A facilitates the welding of titanium, while less than 100 A hinders. On the other hand, the behavior of the cathode point and plasma jet was left without a specific approach.

Toyoda et al. (2003) compared GMAW welding with pulsed current made with a conventional wire-electrode and wire-electrode with a surface layer enriched in oxygen by heat treatment, developed by Daido Steel Co. Ltd. Authors declare that the use of the wire-electrode developed provides the improvement in the slippage of wire-electrode by the rollers of the feeder, promotes stability of the arc, of the metallic transfer, which happens to be regular, smooth and with the drops of the same size and UGPP condition, unlike the conventional wire-electrode.

Shinn et al. (2005) investigated the effect of the low-power laser beam (200 – 300 W) being focused on the front of the fusion pool created in the GMAW process with constant and pulsed current. Results, obtained through high-speed filming, showed that during the use of constant current the cathode point forms on top of the drop in transfer to the melting pool guiding the current through this droplet, favoring the emergence of Pinch effect and, consequently, the formation of splash (Figure 1(d)). Information coincides with the data presented by Salter and Scott (1967), Ries (1983) and Eickhoff and Eagar (1990) and indicates that the passage of current through the droplet in transfer to the melting pool causes generation of splashes during titanium welding/deposition. Still according to these authors the cathode point changes position after each drop is transferred to puddle, which may be responsible for the irregular formation of cord. Figure 2(a) shows the surface aspect of the cord obtained with the GMAW process without the use of a laser aid. In this case the arc preferred to exist with a concentrated cathode point, which suffered the displacement from the lateral to the center of the puddle and presented the cathode jet that was emitted from the melting pool and directed to the right side of the arc, initially being laminar, and after cooling and mixing with ambient air being turbulent. With the auxiliary use of laser beam in the GMAW process, the authors obtained the plasma jet in common shape and fixed cathode point, by restricting it within the laser point, avoiding splashes and promoting the regular and uniform formation of the weld bead (Figure 2(b)). According to Shinn et al. (2005) the additional laser power at the cathode point favors the evaporation of surface material, which can be a stabilization factor of the cathode point. Authors also mentioned the possibility of occurrence of two cathode points simultaneously, one at the top of the droplet in transfer and the other at the original site.

FIGURE 2 – High-speed welding process frames and surface aspect of GMAW welding bead: a) without the use of laser beam; b) with the use of laser beam (adapted from SHINN et al., 2015)

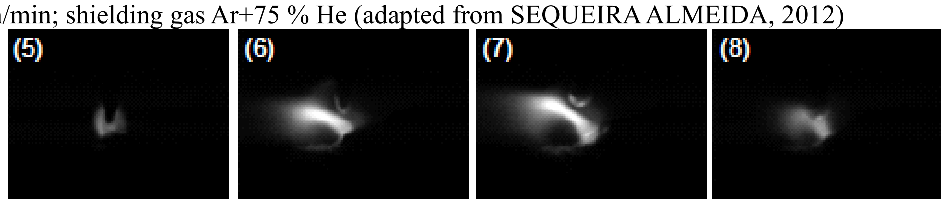


Otani (2007) believes that the cause of the emergence of erratic arc behavior and irregular formation of the weld bead is the facilitated and random emission of electrons per oxide layer on the titanium surface. Author applied a high frequency and low amplitude oscillation of the welding torch in the direction perpendicular to the welding speed direction and managed to stabilize the weld bead. Author believes that addition of 2% of oxygen in argon can favor the regular formation of the cord.

Kapustka (2008), aiming at the realization of additive manufacturing of titanium alloy, used GMAW process with retractive movement of the wire feed along with GTAW process, whose arc was positioned in the front of the melting pool, and managed to solve the erratic behavior of the arc (*wandering*) and improve the geometry of the strands. The work presents the similarity with the idea presented by Shinn et al. (2005).

Sequeira Almeida and Williams (2010a) evaluated the processes GTCAW (Gas Tungsten Constricted Arc Welding, process where arc is constricted through current pulsation in high frequency), GMAW DCEP and GMAW CMT aiming application in Additive Manufacturing of titanium alloy. Authors observed that the GMAW CMT process prevents the mechanism of relocation of the cathode point and, thus, the erratic behavior (*wandering*) of the arc during depositions, favoring the obtainment of uniform layers, of high quality and with reproducibility. However, the Sequeira Almeida and Williams (2010b) apud Sequeira Almeida (2012) presented high-speed footage frames of the arc in the GMAW CMT welding of Ti-6Al-4V (Figure 3), where it can be perceived that the arc is inclined at an angle in relation to the wire-electrode axis. According to the author (SEQUEIRA ALMEIDA, 2012), the complication of the control of the arc column and its direction are caused by the existence of stable but very mobile cathode points. The effect was mainly related to the physical properties of titanium, which determine the mechanism of cathodic emission.

FIGURE 3 – High-speed film frames of the titanium GMAW-CMT welding arc, welding parameters: wire diameter of 1.2 mm; Va of 8.5 m/min; shielding gas Ar+75 % He (adapted from SEQUEIRA ALMEIDA, 2012)



Sun et al. (2015) studied the metal transfer behavior of the titanium alloy Ti-6Al-4V titanium alloy GMAW CMT process. They observed the imposition by the synergistic line of a high-current pulse in the short-circuit phase, which comparatively is close to the open-arc phase current. According to them, this increases the imposition of heat and favors a smooth transfer of droplets, which has relatively high surface tension during titanium welding. Authors tried to perform welding by reducing the high-current pulse in the short-circuit phase by two times, but observed increased instability and occurrence of interruptions. It is understood that increased current in the short-circuit phase is essential for titanium alloy, but at the same time this differs from the classical CMT curve.

In recent years the arc instability in the GMAW process applied to titanium alloys continues to be of high interest, mainly because the GMAW process is highly explored in the Additive Manufacturing sector, for presenting a higher level of productivity and simplicity of execution. Thus, some positive practices acquired for welding in the past are seen to be analyzed for Additive Manufacturing in the present. A highlight: the GMAW process part receives the CMT mode from the manufacturer Fronius.

Sparrow et al. (2019) carried out the work aimed at obtaining the improvements in the deposition of the layers on plate and overlapping layers deposited by Additive Manufacturing of titanium alloy. They used the hybrid method based on laser combination and GMAW CMT mode, which shares the same idea as Shinn et al. (2005). Authors mention that the irregularity of the layer, resulting from the GMAW process, is the direct wandering representation of *the* cathode point and consequently of the process instability itself. As they the energy added by laser in the arc region increases the temperature at the center of the melting pool, creating the hottest point and repressing the cathode point in it, so the arc stops exhibiting wandering behavior. Authors confirmed the achievement of cathode point stability, stability of layer geometry, greater regularity of deposited walls and thus the highest efficiency of deposited material. The addition of laser to the GMAW CMT process also increased the heat tax and unintentionally the deposition rate, so CMT was synergistic. In addition, greater stability of the current and voltage transients was noted, even though the laser and arc sources are independent. The method seems to present a robust and reliable solution, but with a high level of complexity and costs involved.

Kovalenko (2019) performed the CMT mode evaluation work for titanium alloy deposition by Additive Manufacturing and observed the abundant consumption of oxide layer on the surface of the area adjacent to the melting pool, and generation of a relatively large and clean area of the surrounding oxides, which causes occurrence of an unstable arc sequence and arc jet deviations, supposedly looking for oxides. Thus, the absence of oxides in the area near the arc presents itself the reason for arc instability during titanium alloy deposition by the GMAW process, which differs from hypotheses already existing in the literature.

Authors Choudhury, Marya, Amirthalingam (2021) performed deposition work of commercially pure titanium layers, Grade II, on plate and overlapping layers deposited by Additive Manufacturing using GMAW CMT EP and EN. Under these conditions, the authors evaluated the effect of wire with a surface enriched in oxides, from the manufacturer Daido Steel Co. Ltd, sharing the same idea presented by Toyoda et al. (2003). Authors reinforce in their introduction the challenging level of realization of titanium deposition by the GMAW process, presenting as one of the reasons the maintenance of thermionic emission of the material. In this work, the deposition of layers with conventional wire by GMAW CMT EP and EN process was characterized by unstable arc *and* *wandering*, using oscillogram analysis, voltage, cathode point position change recorded by high-speed filming, irregularity and interruption of layer body. While the deposition performed with surface wire enriched by oxides was characterized as stable in all the same aspects. Authors argue, that in reactive materials, such as titanium, cathode point fluctuation is stimulated by oxides present in wire or melting pool, which leads to *wandering*. However, the wire with a surface enriched in oxides forms a uniform layer of slag that helps to form an arc from the melting pool by a shorter path. When observing the results of this work it is evident the increase in regularity of the layer deposited on plate with the use of wire enriched in oxides, but the appearance of the deposited walls did not stand out with the same regularity. Also, it is necessary to remember, that the stable oscillograms of current and voltage of GMAW CMT EP process have already been presented in the literature, as well as regular layers, thus, the data are partially controversial to those previously presented in the literature (SEQUEIRA ALMEIDA, WILLIAMS, 2010a; SUN et al. 2015; KOVALENKO, 2019).

Panchenko et al (2021) carried out the work where they evaluated the GMAW process applied to titanium alloy operating with CMT, CSC and EN polarity modes. In relation to CMT they declared the stable position of cathode point, but at the same time insufficient electrode heating and insufficient formation of the liquid drop at the electrode point. In addition, rare splashes have been reported. However, since the current and voltage oscillogram presented in the study differs from the original CMT mode curve for titanium alloys, the results were not considered representative for titanium and its alloys.

Recently authors Lee et al. (2022) reported obtaining arc stabilization during operation with EN polarity in CMT mode, thus reversing the cathode jet direction from puddle to liquid drop top and thus shifting the cathode jet origin from poça surface to liquid drop top and thus directing it favorably.

3 FINAL CONSIDERATIONS

Based on the information presented, it can be seen that the occurrence of erratic behavior of the cathode point and arc, splash formation and irregular cord are the coexisting characteristics in the GMAW process applied to titanium and its alloys. They were highlighted even in the first scientific works, in the 60's. These characteristics are more frequent for reverse polarity with low constant current, while with high constant current or pulsed current are considerably less manifested. Direct polarity presents extreme instability, so there are no reports of successful application, except for the work of Choudhury, Marya, Amirthalingam (2021) and Lee et al. (2022), all of whom used CMT mode with EN. Several authors have presented their own solution to improve the operability of the GMAW process for titanium. However, the solutions cannot be easily repeated, since they rely on an increase in the level of energy, which is usually harmful or making the process more complex and / or more costly. Regarding the reason responsible for arc instability, the studies have presented the hypotheses, as a function of the properties of titanium, due to the maintenance of thermionic emission, due to the presence of an irregular layer of oxides. However, they do not present the relevant evidence and are accompanied with expressions such as "can be", "seems", "feels", demonstrating the uncertainty involved. For example, the presence of the oxide layer has a beneficial action for aluminum and its alloys, but in most titanium works it was previously removed (Franco-Ferreira and Patriarca, 1959; Wolfe et al., 1965; Kings, 1983). The Shinn et al. (2005) point out that cathode point behavior and arc instability are the relevant phenomena in welding and electric arc deposition processes, but the governing mechanisms are not yet fully understood and their studies are of great interest, as for the field of theoretical foundations so and for the field of practical applications.

REFERENCES

Akulov, A, I. Manual de soldagem. Ed. Engenharia mecânica. Moscou, p. 208, 1971

Choudhury, S.S.; Marya, S.K.; Amirthalingam, M. Improving arc stability during wire arc additive manufacturing of thin-walled titanium components. J. Manuf. Processes 2021, 66, pp. 53–69, doi.org/10.1016/j.jmapro.2021.03.033

Eickhoff, S. T.; Eagar, T. W. Characterization of spatter in low - current GMAW of titanium alloy plate. Welding Journal. v. 69(10), p.382-388, 1990

Franco-Ferreira, E. A.; Patriarca, P. The inert-gás-shielded metal-arc welding of titanium. OAK Ridge National Laboratory. 1959. Relatório técnico.

Kapustka, N. Reciprocating wire feed GMAW additive manufacturing. 2008. Summary report SR0809

KOVALENKO, O. Avaliação de aspectos da estabilidade do arco e da geometria de pré-formas em manufatura aditiva utilizando o processo MIG/MAG CMT com foco na liga Ti-6Al-4V. 2019. 244 f. Tese de Doutorado, Universidade Federal de Uberlândia, MG, Brasil. Disponível em: http://dx.doi.org/10.14393/ufu.te.2019.629

Lee, T. H.; Kam, D. H.; Oh, J. H.; Kim, C. Ti–6Al–4V alloy deposition characteristics at electrode-negative polarity in the cold metal transfer–gas metal arc process. Journal of Materials Research and Technology. doi.org/10.1016/j.jmrt.2022.05.030

Mitchell, D. R.; Feige, N. G. Welding of alfa-beta titanium alloys in one inch plate. Welding Jornal. p. 193-202, May 1967

Nishikawa, W.; Ueyama, T.; Ohnawa, T.; Kondo, A.; Nagata, M., Itoh, R., Yokota, B.; Ushio, M.; Nakata, K. Pulsed MIG welding for titanium. Welding International. v. 14, n. 11, p. 858-864, 2000. DOI: 10.1080/09507110009549283

Otani, T. Titanium Welding Technology. 2007. Nippon steel technical report N. 95

Panchenko, O.; Kurushkin, D.; Isupov, F.; Naumov, A.; Kladov, I.; Surenkova, M. Gas Metal Arc Welding Modes in Wire Arc Additive Manufacturing of Ti-6Al-4V. *Materials* 2021, *14*, 2457. doi.org/10.3390/ma14092457

Pardal, G.; Martina F.; Williams, S. Laser stabilization of GMAW additive manufacturing of Ti-6Al-4V componentes. Journal of Materials Processing Tech. 272 (2019) 1–8. Volume 272. doi.org/10.1016/j.jmatprotec.2019.04.036

Reis, D. E. Gás metal arc welding of titanium. 1983. p. 222. S.M. Thesis. Massachusetts Institute of Technology, Massachusetts

Salter, G. R.; Scott, M. H. The pulsed inert gás metal-arc welding 1 in. thick titanium 721 alloy. Welding Journal. v. 46(4), p. 154-167, 1967

Salter, G. R.; Scott, M. H. The pulsed inert gás metal-arc welding 1 in. thick titanium 721 alloy. Welding Journal. v. 46(4), p. 154-167, 1967

Sequeira Almeida, P. M. and Williams, S. Stable Gás Metal Arc Welding (GMAW) of titanium: the effect of Cold Metal Transfer (CMT) dip transfer mode mechanism on grain refinement. Cranfield

University, School of Applied Sciences (SAS), Welding Engineering Research Centre (WERC), Cranfield. 2010b. Unpublished report.

Sequeira Almeida, P. M. Process control and development in wire and arc Additive Manufacturing. PhD Thesis. Cranfield University. Cranfield. p. 467, 2012

Sequeira Almeida, P. M.; Williams, S. Innovative process model of Ti–6Al–4V additive layer manufacturing using cold metal transfer (CMT). Proccedings of the 21st Annual International Solid Freeform Fabrication Symposium. The University of Texas at Austin, Austin, Texas, USA, p. 25-36, August 9-11, 2010a

Shinn, B. W.; Farson, D. F.; Denney, P. E. Laser stabilisation of arc cathode spots in titanium welding. Science and Technology of Welding and Joining. v. 10(4), p. 475-481, 2005. DOI: 10.1179/174329305X46673

Stark, L. E.; Bartlo, L. J.; Porter, H. G. Welding of one-inch thick Ti-6Al-4V plate. Welding Journal. v. 41(9), p. 805-814, 1962

Sun, Z.; Lv, Y.; Xu, B.; Liu, Y.; Lin, J.; Wang, K. Investigation of droplet transfer behaviours in cold metal transfer (CMT) process on welding Ti-6Al-4V alloy. Int J Adv Manuf Technol. 2015. DOI 10.1007/s00170-015-7197-9.

Toyoda, K.; Noda, T.; Shimizu, T.; Okabe, M. Development of a titanium welding wire for GMAW. Proceedings of the 10th World Conference on Titanium Held at the CCH-Congress Center Hamburg, Germany 13-18. v.1. 2003

Wolfe, R. J.; Hagler, H.; Crisci, J. R.; Frank, A. L. Out-of-chamber welding of Ti-7Al-2Cb-1Ta alloy titanium plate. Welding Journal. v. 44(10), p. 443-456, 1965

Zhang, Y. M.; LI, P. J. Modified active control of metal transfer and pulsed GMAW of titanium. Welding Journal. v. 80 (2), p. 5