Plasma melting: intelligent control strategies

R. Ward, A. Fellows, Thomas Johnson, J. Young, M. Jacobs

► To cite this version:

R. Ward, A. Fellows, Thomas Johnson, J. Young, M. Jacobs. Plasma melting: intelligent control strategies. Journal de Physique IV Proceedings, 1993, 03 (C7), pp.C7-823-C7-828. 10.1051/jp4:19937129 . jpa-00251748

HAL Id: jpa-00251748

<https://hal.science/jpa-00251748>

Submitted on 1 Jan 1993

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Plasma melting: intelligent control strategies

R.M. WARD, A.E. FELLOWS, T.P. JOHNSON, J.M. YOUNG and M.H. JACOBS

The Interdisciplinary Research Centre in Materials for High-Performance Applications, The University of Birmingham, Edgbaston, B15 2TT, U.K.

Abstract

The closed-loop control of a plasma-arc melting furnace was investigated. The different sub-processes were found to be highly coupled, and the available sensors and actuators were insufficient. Both of these factors increase the difficulty of controlling the process. A control system design is shown which combines groups of sensor readings by using the available knowledge about the process to generate new variables which are more directly relevant to the control of the system. This new information, even if not used in a control system, is useful to the operators. The benefits of closed-loop control are discussed.

Introduction

Cold-hearth plasma-arc melting (PAM) is emerging as a potentially important route for production of high-quality alloys for the aerospace industry, amongst others. The PAM process has been found to produce ingots with good chemical homogeneity, and does not suffer from evaporation of high vapour pressure elements as it operates under nearly atmospheric pressure [1]. This makes the PAM process particularly suitable for the primary processing of intermetallic materials such as titanium aluminides. The chief aim of this paper is to show that although the cold-hearth melting of reactive metals does present some difficulties to the development of a closed-loop control system, these difficulties can be overcome, and that closed-loop control can contribute to the quality control of products.

Figure 1: the plasma furnace

The furnace at the IRC, a schematic of which is shown in figure 1, is capable of producing ingots of 100mm and 150mm diameter, and up to 1.4m in length. It is powered by two 150kW servo-hydraulic, computer-controlled transferred-arc plasma torches which use helium as the plasma gas. One torch melts feedstock into a water-cooled copper hearth with the initial formation of a skull. Liquid metal then flows over the skull from the hearth into a water-cooled copper crucible with a retractable base to form a continuous ingot.

Before melting commences, the furnace is evacuated to a pressure of $<40\mu$ bar. Provided the leak up rate is $<3\mu$ bar/min, the furnace is then back filled with argon to a pressure of 1.1 bar, which is maintained throughout the melting process.

The goals for the PAM process will depend partly on how the produced ingots are to be further processed - a bar for remelting does not need a good surface finish, but one for forging does. The possible goals include chemical homogeneity, removal of inclusions, a flat surface and controlled macrostructure and microstructure. For example, the ability to control the macrostructure in a Ti - 48 Al - 2 Mn - 2 Nb alloy is useful, because the orientation of the lamellae has a strong effect on the flow stress [2], and hence on the response to post-processing procedures such as forging [3].

The goals can only be achieved through interaction with the process using the available sensors and actuators. Quantities which can be sensed on the IRC PAM furnace include the torch currents, voltages and gas pressures, the temperature of a point on the melt pool surface, and the coolant temperatures etc. Actuators which can be used include positioning the torches, controlling the torch parameters, adding feedstock and withdrawing the ingot in the crucible.

Process monitoring to measure product consistency,

One of the ultimate goals of any refining process is the removal of unwanted inclusions which can act as crack initiation sites. Keeping all inclusions to less than a certain size has been shown to improve low cycle fatigue life for nickel-based alloys.[4], this will almost certainly be true for titanium alloys. As the size of these inclusions decreases, they become progressively more difficult to detect, and only destructive methods (such as low-cycle fatigue testing) become effective. Thus, as it is not possible to test the material which is actually going to be used to make a component, there is no real alternative to statistical quality assurance, which relies on being able to produce consistent material. (One or more samples from the product can be assessed for the important properties, and the probability density function of the properties' distributions determined. The size of the whole batch can then be used to predict the maximum variation in properties to a given confidence level, e.g. 99.9%). If the process is not monitored to show that the product is consistent within itself, then many samples may need to be destructively tested to ensure that no areas with poor properties are left. If process monitoring is to be used, then it is necessary to determine what the necessary variables to monitor are and then to be able to monitor them. Collaboration between users, producers and researchers may be needed to determine what the necessary variables are [5]. Work also needs to be done to develop the sensors to monitor them [6], as processes involving high temperatures and reactive metals are difficult to monitor.

Process monitoring to measure product quality

The idea of monitoring the process to assure that the products made contain no regions with different, possibly poor, properties can be extended to monitoring the process to assure that the products made, as well as being consistent, are of the required high quality. If it can be shown that, provided the monitored variables stay within certain prescribed ranges then the product is likely to be of a certain quality, then nearly all of the need for further destructive testing is removed.

Process control to assure product quality

Once it has been decided to maintain certain variables within certain ranges during production in order to assure quality, then the advantages (such as repeatability and accuracy) of an effective control system become more apparent. The control system maintains the necessary variables within the prescribed ranges, as far as is possible, thus producing material of assured quality.

Unfortunately, the closed-loop control of the PAM process is made more difficult by the lack of suitable sensors and actuators. Åström and Wittenmark [7] mention the need for sensors and actuators which correspond as closely as possible to the important process variables. For example, melt-pool size, shape and position are thought to be important [8], but can not currently be measured (but see [9] for a possible technique based on laser-generated ultrasonic waves in the melt-pool). The process is also highly coupled - most parts of the process can not be controlled in isolation, as they affect and are affected by other parts of the process. For example, sweeping more material into the crucible to maintain the melt-pool shape reduces the level in the hearth, affecting inclusion removal processes, and also occupies the torch which

might otherwise be melting the feedstock. Many of the relationships between parts of the process are not known analytically (i.e. by physical relationships) or even in model form, and only rules-of-thumb (heuristics) are available. These problems in controlling the PAM process point to the need for a flexible control system which can ideally use the knowledge that is available about the process - an 'intelligent' control system. A diagram of the structure of such a system is shown in figure 2:

Figure 2: The furnace and control system

The signals from the sensors and to the actuators are referred to as 'low-level' variables, and the goals of ingot production are referred to as 'high-level'. The 'intermediate level' refers to variables which are not directly measurable from single sensors, but are inferred from combinations, by 'observers'.

In order for the control system to achieve its goals, the relationships between the goals and the sensors and actuators must be known. A useful step is to identify intermediate-level variables, which can be linked to both the high-level goals and the low-level sensors and actuators. For the plasma melter, for example, the position of the top of the melt-pool in the withdrawal crucible and the depth and shape of the melt-pool are thought to be important, as they can be linked to surface finish and also to low-level variables.

Once these relationships are known, they have to be incorporated into a control system. The idea of state space control can be used here. (The 'state' is the smallest group of process variables which, along with knowledge of the future system inputs, can be used to completely predict the system's future behaviour.. State space is simply the coordinate system where each element of the state forms one dimension - thus every possible state that the process can be in is a unique point in state space. State space and other control techniques are described in [7]). Strictly for a system to be controllable by the state space technique, the state variables chosen must completely describe the system, and the system must also be observable - i.e. it must be possible to determine the values of the state variables from the inputs and outputs in a finite amount of time. In the terminology of state-space control, when a state variable is not directly measurable, an 'observer' can be used to generate it based on a combination of inputs or outputs.

Some process variables (such as the temperature of every point in the melt-pools) can either not be measured, or are subject to uncertainty - recent developments in robust identification and control are applicable in these situations [10]. It must be possible to relate all the state variables chosen to sensors (by observers) and actuators. This is where the intermediate-level variables mentioned earlier can be used - as state variables. The relationships between the sensors and the intermediate-level variables are the observers. Any requests for actions generated by the controller based on the (intermediate-level) state

variables then need to be translated into physical operations, such as increasing the crucible torch current to deepen the crucible melt-pool. For the plasma melter, both the observers and the ways of translating from controller requests to physical actions may be heuristic, model-based or analytic.

Example observers - determination of melt-pool depth and position

As was mentioned previously, the positions of the melt-pools in the crucible and the hearth and their depths are thought to be important state variables. It may be possible to calculate melt-pool depth either by running a heat-transfer model in real time, or by using a simpler correlation based on off-line modelling work. Either method could use the torch power, torch positions, melt surface temperature and withdrawal rate as inputs. The level of metal in the hearth and crucible can be calculated in at least three ways: in order of increasing cost and increasing effectiveness - by determination of the arc length and knowledge of the position of the torch tip (free, except for the cost of doing trials); by video camera (£2,000 for frame-grabber + camera); and by laser range-finder (approximately £7,000 for off-the-shelf equipment). The determination of melt-pool position by torch arc length will be discussed in greater detail.

The combination of plasma torches and power supply at the IRC has a negative dynamic resistance [11] - the voltage across the arc decreases as the current increases, except for short-term (ms) fluctuations. The voltage is also affected by the torch gas pressure, and the length of the arc. A series of trials was undertaken where the arc length (distance from torch to melt-pool), current and gas pressure were systematically varied - the results of one of these are shown in figure 3. The true arc length was determined by adding the height of the torch to the distance between the torch's zero height point and the top of the ingot used - this can only be done when the furnace has cooled down and the actual position of the ingot can be measured. By combining the expected negative resistance of the arc and the knowledge gained from plotting graphs of the relationships between the data from the trials, a parametric relationship between current, length, gas pressure and voltage was obtained. This was then inverted to produce a function which could predict the length of the arc from the torch tip to a surface, by using the arc voltage, arc current and gas pressure. The predicted arc length for the data in figure 3 is also shown:

Figure 3: a graph of arc length, torch current, torch voltage, gas pressure, and predicted arc length for a Ti - 48 Al - 2 Mn - 2 Nb alloy.

The parameters for the arc-length model were determined by a combination of least-squares fitting and a search routine, as the relationship was partly non-linear in its parameters. For validation, the model was also used to predict the arc-length for trial data which had not been used for development of the relationship. The results are shown in figure 4: the agreement between the predicted arc length and the post-hoc measurement is quite good.

When the relationship was used on the data from which it had been derived, the errors between the post-hoc measured arc length and predicted arc length had an RMS of 0.22", or 0.11" if the mean of 10 samples were taken for each point. The results on fresh data had an RMS error of 0.17" (after removal of a mean offset) although a smaller pressure range was covered in this data set than in the training data set. If the mean of 10 samples was taken for each point, the RMS error fell to 0.13".

Once the arc length is known, it can be combined with knowledge of where the tip of the torch is, in order to predict the position of the metal surface with which the arc is in contact (i.e. the level of metal in the crucible or hearth). In practice, areas of weakness were found when this technique was used to predict the level of metal in the crucible during ingot production. The arc itself is in contact with more than just the surface of the solidifying ingot - especially in the 4" diameter crucible, it is also effectively in partial electrical contact with the copper crucible walls. Thus the length of arc 'seen' is not just the distance from the torch to the ingot. This problem can be partly avoided by calculating arc length only when the torch is in the centre of the ingot (i.e. as far away from the walls as possible), but the measurement time required to generate an accurate stable reading was excessive, and disrupted the necessary torch movement patterns. The relationship was also found to give errors when applied to mostly Ti-based alloys (e.g. IMI 318, cp titanium), which may be due to their having different fall voltages [1], and was affected by the electrical field of the stirring coil in these cases.

Figure 4: the results of using the relationship to predict arc length using a Ti - 48 Al - 2 Mn - 2 Nb alloy for a new set of data, after removal of mean offset

For this reason, a technique based on image analysis is under development for the determination of metal level in the crucible. For the hearth, further trials of the arc-length technique are to be undertaken, as the problems caused by the copper walls and stir-coil should not occur there.

Discussion

The proper process monitoring essential for a computerised control system is also extremely helpful for operators, and can improve their performance while a control system is being developed, by providing higher-level information than would normally be available from basic instruments and visual monitoring. It may still be the case that some aspects of the PAM process are most economically controlled by people, such as spotting 'fingers' of metal linking a refining hearth to the withdrawal crucible. This is because humans are very good at analysis of unstructured images. Other functions, such as maintaining the levels of molten metal in the hearth(s) and crucible, are probably best undertaken by computer due to the need for repetitive accurate calculations.

Like many processes, when everything is going well only a minimal amount of control is needed for PAM - it can almost run successfully in open loop. Once things go slightly wrong (e.g. the level of metal

in the crucible drops) then the control system has to choose its actions from sweeping more material from the hearth, melting more feedstock, or slowing the withdrawal in the crucible. All of these actions may affect important aspects of the produced ingot, so they must be chosen carefully. If things go badly wrong (e.g. there is a 'weld-up' caused by compacted feedstock falling partially into the hearth) then the quality of the withdrawing ingot needs to be protected until the situation can be remedied, and so considerable control action is needed. Careful design of the physical layout of the PAM process and feedstock can help in removing some of the difficulties of process control.

Conclusions

1. A control and monitoring system can help to produce material of consistent and assured quality, but discussion with users is necessary to ensure that the correct goals are being worked at.
2. The various parts of the PAM process are highly coupled, which must be taken account of when designing a control system.
3. It is difficult to make sensors and actuators for the PAM process, due to the aggressive environment.
4. In order to link some of the available sensors and actuators, intermediate variables can be generated, such as melt-pool depth and position. These intermediate variables are not accessible by single sensors or actuators, but are generated from groups by observers, which may be heuristic, model-based or analytical.
5. Making these intermediate-level variables available to the operators, even before the control system to tie them together is available, can make their job easier.
6. A combination of intermediate and low-level variables can be used to describe the state of the system, which can then be used with the ideas of the state space control technique to produce a control strategy.
7. The overall control system has to cope with both quantitative disturbances (e.g. the level of metal in the withdrawal crucible falling by a certain distance) and qualitative disturbances (e.g. the welding-up of the feedstock), and react accordingly.
8. Careful physical design of the process can make control easier.

Acknowledgements

The authors would like to acknowledge the help and support of Professor M.H. Loretto and also the financial support of the UK. Science and Engineering Research Council. They are also indebted to the considerable efforts and technical support of the whole of the plasma melting team.

-
- [1] KNIGHT, R., SMITH, R.W. and APELIAN, D., "Application of plasma arc melting technology to processing of reactive metals", *International Materials Reviews*, **36**,6 (1991) 221-254
 - [2] YAMAGUCHI, M. and UMAKOSHI, Y., "The Deformation Behaviour of Intermetallic Superlattice Compounds" *Progress in Materials Science*, **34** (1990), 1-148.
 - [3] JOHNSON, T.P., YOUNG, J.M., WARD, R.M. and JACOBS, M.H., "Influence of Melting Conditions on Structure and Quality of Plasma Melted Titanium Aluminides", (Proceedings of *International Symposium on Structural Intermetallics at Seven Springs*, September 26-30, 1993)
 - [4] PATEL, S.J. and ELLIOTT, I.C., "Production of High-Strength P/M Disc Alloys by "Superclean" Cast/Wrought Technology", *Superalloys 1992*, ed. S.D. Antolovich et al., The Minerals, Metals and Materials Society, 1992
 - [5] MITCHELL, A., *ISIJ International* **32**,5 (1992) 562
 - [6] SHAMBLEEN, C.E., BUTTRILL, W.H. and HUNTER, G.B., "Titanium Alloy Hearth Melt Technology", *7th World conference on Titanium*, 1992
 - [7] ÅSTRÖM, K.J. and WITTENMARK, B., *Computer Controlled Systems: Theory and Design*, USA, N.J.: Prentice-Hall, 1984
 - [8] JOHNSON, T.P., JESPER, N.E., YOUNG, J.M., WARD, R.M. and JACOBS, M.H., "The Microstructure of Plasma Arc Cold-Hearth Melted Ti-48Al-2Mn-2Nb", (Presented at Euromat 93: The 3rd European Conference on Advanced Materials and Processes, Paris, June 1993)
 - [9] BLACKBURN, M.J. and MALLEY, D.R., Plasma Arc Melting of Titanium Alloys, (Paper presented at IRC'92 - Processing, Properties and Applications of Metallic and Ceramic Materials, Eds. M H Loretto and C J Beevers, MCE Publications Ltd., September 1992)
 - [10] NORTON, J.P. and VERES, S.M., "Developments in Parameter Bounding", pp. 137-158 in *Topics in Stochastic Systems: Modelling, Estimation and Adaptive Control*, L. Gerencser and P.E. Caines, Eds., from the series *Lecture Notes in Control and Information Theory*
 - [11] FEINMAN, J., (ed.), *Plasma Technology in Metallurgical Processing*, USA, Warrendale, PA: The Iron and Steel Society, 1987