# Thermal-pulsed MIG/MAG welding applied to the repair of cavitation erosion on large-scale hydraulic turbines

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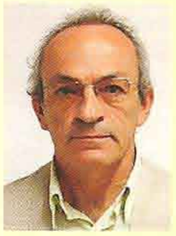

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**In power generation at hydroelectric power plants, the elements are massive, as well as the arising problems. One such problem which often causes significant loss of revenue is turbine blade wear due to a process known as cavitation erosion. The wear process is kept under control through the replacement of the removed material by means of welding processes. An industrial project partner of UFSC (Federal University of Santa Catarina) has suffered from stoppages lasting 15 to 30 days at its largest power plants due to this type of maintenance. With the aim of minimising this work, a new procedure which substitutes stick electrodes by thermal-pulsed MIG/MAG welding was developed in order to ensure a reduction in defects, a better weld quality and a noticeable increase in productivity. Commercially available equipment did not offer the conditions and flexibility required for the research which demanded software development in addition to welding procedure formulation. The developed equipment and consumable-oriented welding procedure were implemented industrially and gave benefits which continue to the present day.**

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## 1 Introduction

Large-scale hydraulic turbine blades, Fig. 1, suffer from a phenomenon known as cavitation erosion, Fig. 2, since, despite advances in numerical modelling techniques in fluid mechanics, it is still not possible to completely avoid this problem which is caused by pressure waves resulting from the implosion of bubbles. On older turbines which will continue to operate for at least half a century, this problem is more serious, their replacement being economically unviable and technically complex. Thus, the erosion process must be kept under control. This can be achieved through the deposition of material by means of welding processes. That requires quantities in the order of 1,000 kg of special stainless steel alloys for each turbine.

The eroded areas usually appear in positions which are unfavourable with regard to welding, both in terms of the comfort for the welder and of the adhesion of the molten metal during its transfer from the electrode to the turbine surface.

The quality of the welding procedure, which must be set in deep accordance with the properties of the welding consumable and welding conditions (regarding mainly welding in the overhead position), is a critical point in this work. If the process is not carried out according to strict criteria, material deposition may still be carried out with good productivity with MIG/MAG but the resistance to cavitation of the deposited layer may be way below the specifications. An important matter regarding the quality of the deposited coating is the presence of porosities which are core points where the removal of material by the cavitation phenomenon starts. Laboratory tests have shown a strong dependence between the homogeneity of the surface and the resistance to cavitation [1]. Both the occurrence of porosities and homogeneity deficiencies depend mostly on the characteristics of the metal transfer and the weld pool stability.

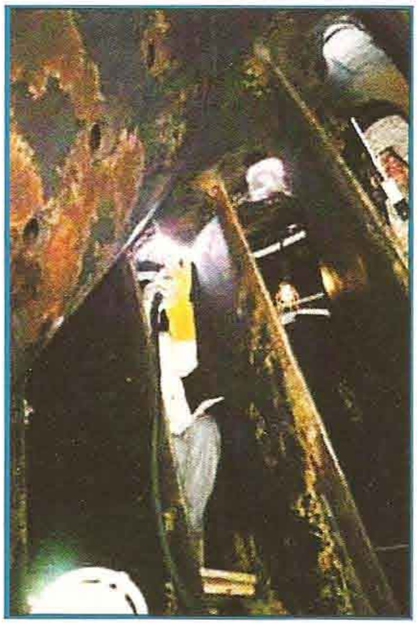

*Fig. 1. Welder between the blades of a hydraulic turbine in a power generation unit.*

One of LABSOLDA/UFSC's industrial project partners, acting on hydroelectric power generation, used to carry out the repair of eroded areas using stainless steel (ASTM 309) and cobalt-base stainless

*Fig. 2.* Cavitation-eroded area in detail.

steel stick electrodes. In both cases, the productivity was low, thus implicating high costs and time demands. Thus, the necessity arose to change over to the use of continuous tubular wires using the MIG/MAG process. However, the company encountered serious difficulties regarding the weldability of these wires when using conventional CV MIG/MAG. The deposits were irregular and had a great quantity of porosities. This fact led to the need for significant material removal through grinding in order to shape the surface. The entire process was therefore very time-consuming, causing several hours of turbine downtime and losses of millions of Reals (Brazilian currency). Furthermore, since the deposit had a lot of defects, its resistance to cavitation was lower than expected.

In view of these problems, the global goal was to optimise the overall productivity by developing a new procedure which substitutes stick electrodes by thermal-pulsed (also known as double-pulsed) MIG/MAG welding in order to ensure a reduction in defects, a better weld quality, the feasibility of overhead welding and a noticeable increase in deposition efficiency. As commercially available equipment did not offer the conditions and flexibility required for the research, the activities resulted in novel welding control software attached to welding procedure formulation, both specifically dedicated to the new consumable.

## 2 Factors regarding coating alloys

Although most hydraulic turbines are made of standard carbon steel, the weld deposits for the repair of eroded areas are carried out with noble materials, aiming at a greater durability of the coated areas. The utilisation of hard alloys has, however, led to problems with cracking which affects the quality of the deposits.

The current worldwide status of materials technology development has led to the development of austenitic cobalt (Co) alloys, specifically resistant to intense cavitation conditions. Despite being austenitic alloys which present ductility, they suffer surface hardening due to the effect of surface work. It could be said that the alloys self-harden in an intelligent way.

Some hypotheses have been proposed in order to explain this increase in hardness. One of them is based on the surface hardening mechanism associated with the phase transformations $\gamma \rightarrow \alpha'$ and/or $\gamma \rightarrow \varepsilon$ caused by deformations originating from bubbles collapsing against the surface and microjets. A reduction in the material loss rate was observed in relation to 308 stainless steel leading to an increase in the working life of the equipment [2]. The mentioned cobalt alloys were initially supplied only in stick electrodes. Due to their very nature, this leads to low productivity. The launching of these alloys in the form of wires for the MIG/MAG process has been made viable only in a tubular form, due to the hardness of the material. Table 1 [3] shows the chemical composition.

The weldability of the wire electrode, from the operational point of view, was found to be problematic, implying a poor finish, fusion defects and, above all, too much porosity. Thus, the excellent quality of the material in relation to cavitation resistance was seriously compromised. In addition to that, the cost of such wires in Brazil may reach ten times the price of conventional stainless steel wires. These difficulties have led power generation companies either to give up on the use of such wires or to decide not even to start on the subject.

*Table 1.* Chemical composition of the cavitation-resistant alloy [3].

| C % | Mn % | Si % | Cr % | Co % | N % |
|---|---|---|---|---|---|
| 0.2 | 10 | 3 | 17 | 9 | 0.2 |

## 3 Developments for MIG/MAG welding with cobalt-base wire electrodes

Due to the operational difficulties of the MIG/MAG process using cobalt-base wire electrodes, LABSOLDA/UFSC, with the support of an industrial partner, developed a complete technique, including equipment, which revolutionised the application of cobalt wires by means of the MIG/MAG process for the repair of hydraulic turbines.

The basis of this technique is associated with the advantages of current pulsation which can be achieved in both the MIG/MAG and TIG processes. This is why the process is called thermal-pulsed MIG/MAG or double-pulsed MIG/MAG welding. The pulsation of the current at a frequency compatible with the formation of droplets at the end of the wire electrode (starting at 30 Hz) aims at controlling the metal transfer, producing a stable arc. When the average current resulting from this pulsation is also varied (pulsed) in such a way as to produce thermal cycles, as occurs in the pulsed TIG process (in the range from 0.5 to 2 Hz), an adequate and sustained molten pool is achieved.

The equipment developed to supply this welding system, apart from controlling the above-mentioned thermal cycles of the welding, offers the possibility to set different values for the current in order to provide an initialisation phase as well as an end phase.

These respective phases are controlled by the welder through the trigger button on the torch. When the welder keeps the button pressed down, a pulsed current without thermal oscillations is established. At the moment when the welder releases the button, the steady state is established. This has current oscillations between high average values (thermal pulse) and low average values (thermal base). The end phase begins at the moment when the welder pushes the button again and ends when he releases it, Fig. 3. Fig. 4 shows a real oscillogram of the thermal-pulsed MIG/MAG process.

## 4 Results and discussion

### 4.1 Influence on the deposited layer

Due to the action of the thermal cycles, an agitation in the metal pool is produced, making the chemical elements inside the wire, in form of powder, mix adequately with the wire cap. The same agitation effect expels the dissolved gases, eliminating porosities. High-energy cycles act so as to eliminate the lack of fusion while the low-energy cycles are responsible for the adequate sustentation of the molten bath in the overhead position. From the visual aspect, the deposit is superior to that resulting from the conventional MIG/MAG process, as can be seen on Fig. 5. Table 2 shows the parameters for the double-pulsed MIG/MAG procedure. As the welding source is provided with synergic control, just the average currents of the thermal pulse and thermal base have to be adjusted.

The better surface condition makes the shape operation (grinding) easier and less material is wasted. Also, the reduction of spatter means less downtime for torch cleaning as well as more comfort and safety for the welder.

### 4.2 Comparative performance of several processes concerning cavitation resistance

Further comparisons were made in order to assess the benefits of double-pulsed MIG/MAG with cobalt-base wire electrodes considering other processes and consumables. Fig. 6 shows the cumulative loss of mass curve of several coatings subjected to an accelerated cavitation test. The Fe-Cr-Mn-Ni alloy and the LO3 alloy were deposited by means of PTA welding. The Cav Plasma sample was deposited with plasma arc welding and the same cobalt-base wire electrode as the double-pulsed MIG/MAG sample (Cav MIG). The E 309 sample was welded with pulsed MIG/MAG welding and the AISI 304 0.48% Ni sample was nitrided at a high temperature [4]. As can be seen, the double-pulsed MIG/MAG procedure is superior.

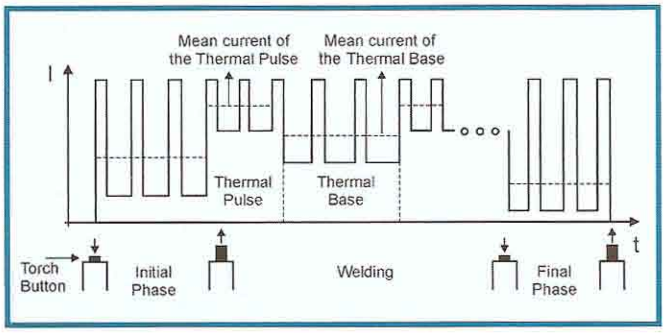


*Fig. 3. Idealised oscillogram of double-pulsed MIG/MAG welding.*

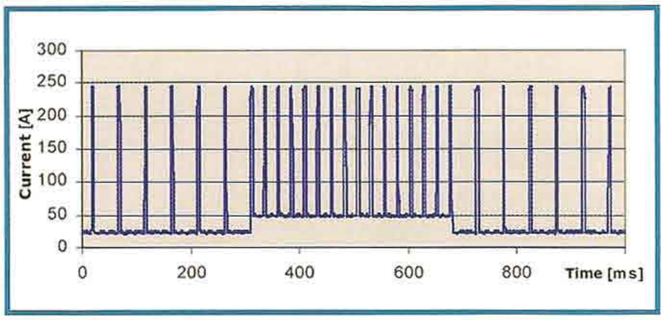


*Fig. 4. Real oscillogram of the thermal-pulsed MIG/MAG process.*

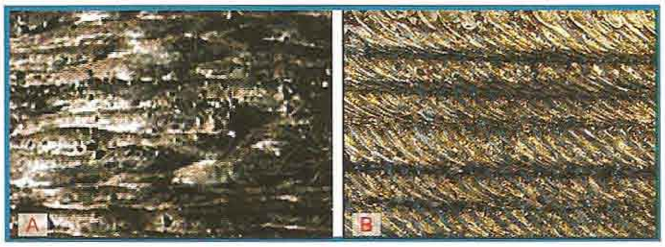


*Fig. 5. Conventional **(A)** and double-pulsed **(B)** MIG/MAG welding deposits.*

*Table 2. Welding parameters for thermal-pulsed MIG/MAG welding.*

| | |
|---|---|
| Thermal pulse current (Ip) | 170 A |
| Thermal base current (Ib) | 100 A |
| Thermal pulse time (tp) | 0,5 s |
| Thermal base time (tb) | 0,5 s |
| Welding speed | 20 cm/min |
| Shielding gas flow | 15 l/min (95% Ar + 3% $CO_2$ + 2% $N_2$) |

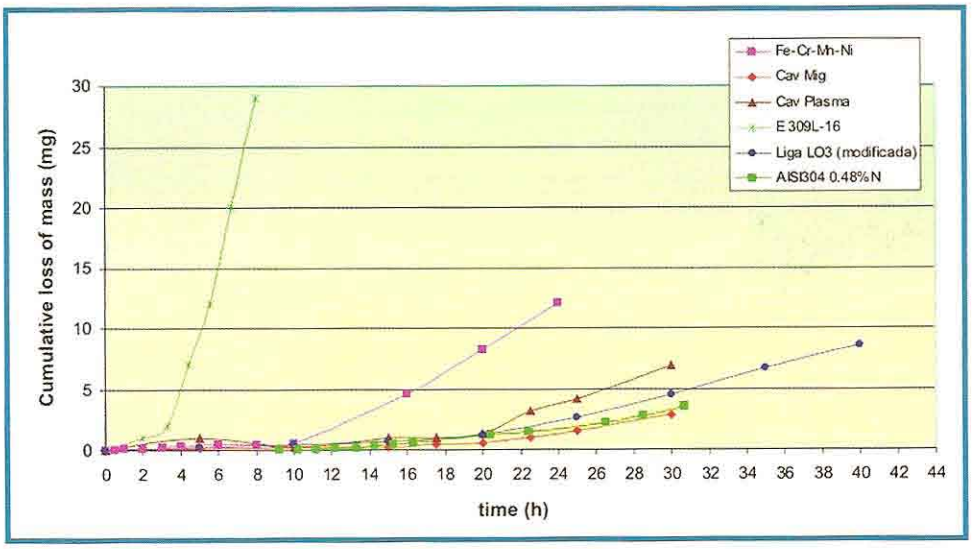


*Fig. 6.* *Cumulative mass loss for the double-pulsed MIG/MAG welding with commercial wire (CAVMIG sample) compared with other alloys and deposition processes.*

In addition to the accelerated cavitation results, it must be mentioned that the double-pulsed MIG/MAG process is still more robust than PTA for this application, in terms of the ease of welding (control of the molten pool) and the number of parameters to adjust.

## 5 Conclusions

This industrially oriented research was successful and practical implementation has already been carried out in the project partner company. The impact has been significant since the interval between repair stoppages increased by 50% and even by 100% in some cases. The double-pulsed MIG/MAG process went through an evaluation period and was consolidated as the process for the repair of hydroelectric turbines eroded by cavitation in several plants, given its high productivity.

Concerning the benefits of the results, the increase in productivity must be regarded in a global way. Not only process-related advantages (good deposition rate and efficiency, continuous material feeding) must be considered. The higher quality (absence of defects, spatter reduction, better surface shape) additionally provides less downtime (rework, torch cleaning, excessive grinding) and augments the durability of the coating.

The work also resulted in the development of a flexible welding source with open control software and hardware which permits the extension of the usage of the double-pulsed MIG/MAG and other arc welding processes to several different applications.

**Literature**

[1] Boccanera, L., et al.: Influência do Acabamento Superficial, Porosidade e Diluiçao sobre a Resistência à Cavitaçao de Revestimentos Soldados, XX ENTS, Fortaleza/Brazil, 1998.

[2] Barra, S. R.: Influência dos Procedimentos de Soldagem sobre a Resistência à Cavitaçao de Depósitos Obtidos com a Utilizaçao de Arames Tubulares de Aços Inoxidáveis Ligados ao Cobalto, Masters Dissertation, EMC/UFSC. Florianópolis/Brazil, 1998.

[3] Hart, D., and D. Whale: A review of cavitation erosion resistant weld surfacing alloys for hydroturbines. Proceedings Asian-Pacific Welding Conference, Auckland/New Zealand, 1996.

[4] Buschinelli, A. J. de A. Development of cavitation resistant alloys. Internal Report, UFSC. Florianópolis/Brazil, 2008.