Methodology for embedding mineral insulated cables into DIN 1.2311 tool steel for the manufacture of smart tooling

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Abstract: In the present climate led by industry and digital manufacturing, the implementation of intelligent tooling in manufacturing processes has become imperative. In the case of metal forming processes, this requirement is translated into controlling the material flow and the temperature in the tool-part contact interface. In this manner, not only the mechanical properties of the produced parts are predicted, but also the status of the tooling can be monitored. To that end, a methodology for embedding sensors close to key areas needs to be developed. Additive Manufacturing holds a great potential for enabling such integration. However, high process temperatures inherent to metal AM processes are a limiting factor in this matter. With the aim of taking a step forward in this field, in the present work a methodology for embedding mineral insulated cables into metal forming tooling has been developed. Furthermore, the minimum cable size integrable by means of this technology has been determined and the main limitations of this process exposed. It has been concluded that low energy inputs are necessary to avoid the destruction of the sensorial components and that adaptive process parameters are necessary if sound metal coatings over undamaged components are to be deposited.

Keywords: Embedded sensor, Laser Direct Energy Deposition, Industry 4.0, Smart tooling, Metal forming.

1. Introduction
The current mood of the manufacturing industry is highly defined by the Industry 4.0 and digital manufacturing context, as these tools have the potential of increasing the flexibility in manufacturing and permitting mass customization [1]. Moreover, it pledges to enhance the quality and to improve productivity of manufacturing processes [1]. One of the main goals of the Industry 4.0 relies on factories evolving into automated facilities, which make intelligent decisions based on real-time collected data [2]. However, in order to achieve the aforementioned goals, certain underpinning manufacturing technologies are required, which allow devices and manufacturing systems to adapt their behaviour according to each particular situation [1].

A key aspect of the Industry 4.0 era, which should be highlighted, is the fact that implementing online monitoring systems in manufacturing processes is imperative if traceability and product quality are to be ensured [3]. For that end, sensing technologies need to be integrated into the manufacturing systems and components. These systems are able to collect data in a real-time manner, and to detect and quantify any changes that occur in the working environment, which can be further processed and minimized by...
a close-loop control system [4-6]. Nonetheless, the application of these advanced technologies to the real industry is not without its challenges. In the case of the die and mould industry, integrating sensors in critical areas of the surface and cavities could be a step forward in this direction [7], as it would permit measuring essential parameters at the points of interest [6]. The motivation for the acquisition of this data is driven by two main objectives. Firstly, to identify the incorrect behaviour of the forming process, enabling early detection of potential failures in production [8]. In fact, the physical properties of the final part can be determined by monitoring the material flow and the temperature at the tool-part contact interface. Secondly, to predict the failure of the tooling, as real-time data acquisition provides information of its health status [9]. However, a major challenge when realising smart tooling for metal forming processes is the embedment of sensors in the dies and moulds itself. Consequently, currently control systems in metal forming processes rely on sensors located away from the contact region of the moulds [10]. Thus, the implementation of smart tooling in the metal forming industry still remains marginal [8].

Additive Manufacturing (AM) holds the promise of providing a successful method for embedding electronics in functional parts. According to Thompson et al. [12], tooling for metal forming processes can be manufactured by means of hybrid additive manufacturing, which allows complex features to be printed on top of the parts and functional features to be embedded within printed parts. Moreover, AM processes enable accessing the component at intermediate manufacturing stages [13]; thus, it gives additive technologies leverage, in terms of the manufacture of tooling with integrated sensors. Among all the AM processes available, Directed Energy Deposition (DED) is considered the best suited for sensor integration in metal components [14]. Its incremental layered manufacturing principle provides complete access to the internal geometry of the components to be manufactured, enabling the placement of sensors close to the points of interest before enclosure [15].

In addition, powder-based laser DED (L-DED) is widely employed for die and mould applications, mostly for repair and coating purposes. Moreover, driven by the rapid evolution of L-DED processes, new opportunities open up, such as the possibility of fabricating tool steel parts, whose geometric complexity prevent conventional processes from being suitable [16]. This fact has led to the risen popularity of L-DED process for manufacturing tooling for metal forming processes [17].

In the L-DED process, a laser is focused into a surface, where the melt pool is formed, while feedstock in the powder form is simultaneously injected into it. When the metal solidifies, a clad is formed, which properly overlapped lead to a layer of added material. This process takes place in an inert atmosphere created by the shielding gas, which avoids material oxidation.

In this manner, the following steps may be followed to embed electronic or mechanical components by means of L-DED [19]:

- Step 1: the deposition process starts, and successive layers of metal are deposited.
- Step 2: after a certain number of layers have been deposited, the process stops, and the sensor is located in the predetermined location.
- Step 3: the deposition process is resumed, and the remaining layers are deposited onto the sensor, until the desired geometry is achieved.

However, embedment of sensors by means of L-DED is not a trivial matter. Although embedment of components in polymer structures has been reported in the literature since the 1990s [12], many difficulties arise when attempts to integrate functional components into metal parts are made. The manufacture of sensor-integrated metal forming tools is limited by the high processing temperatures inherent in the metal AM processes. Temperatures well above 1300ºC have been reported in L-DED of metallic materials [20]. Such a high energy input in the proximity of electronic components often leads to their destruction [20]. Therefore, in order to overcome the mandatory thermal processing intrinsic to the L-DED process, sensor materials need to be protected during the deposition process [15]. In this manner, their survivability is ensured. Another strategy to address this issue consists in using multiple deposition parameter combinations during the L-DED process [20], so that the energy input and the
subsequent processing temperatures are controlled. For instance, Petrat et al. [20] studied the integration of electronics into metallic parts using L-DED and L-PBF, and found that by adapting the process parameters in the surroundings of the electronic components, successful integration could be achieved. Juhasz et al. [12], on the other hand, developed a proof-of-concept in which they integrated a strain sensor into a tensile bar by means of L-DED. Regarding die and mould applications, Martinsen et al. [7] developed a methodology to integrate temperature sensors in injection moulding dies by means of Direct Write Thermal Spray.

To conclude, it is out of dispute that sensor integration for tooling in metal forming applications has risen interest in the current digital manufacturing era. In addition, it has been found that although attempts have been done to embed sensors into metallic components, there is still a need for a consistent methodology to manufacture sensor-integrated tooling by means of L-DED. It is this context which has motivated the present work, where the integrability of thermocouples in hot stamping dies has been assessed. Therefore, a methodology for embedding mineral insulated (MI) cables into DIN 1.2311 tool steel has been developed, validated, and the deposition strategies optimised.

2. Methodology

2.1. Materials and equipment

The experimental setup consists of a 5-axis Yb:YAG fibre laser processing machine with a 1 kW maximum power and a 1.8 mm laser spot, a rotary powder-feeder, and a coaxial nozzle.

As far as the materials are concerned, DIN 1.2311 and 1.2344 tool steels have been used as substrate and L-DED coating, respectively, and their composition is detailed in table 1. The dimensions of the substrate are 100 x 80.6 x 25.8 mm³ and semi-circular grooves have been machined on its surface, so that it can accommodate the MI cables, as depicted in figure 1(c). The components to be embedded, on the other hand, are MI cables of diameters 3, 4.5, 6.5 and 8 mm, as shown in figure 1(a). Also, in figure 1(b), the internal structure of the MI cables is schematically represented. Finally, figure 1(c) shows the scheme of an embedded MI cable.

| Table 1. Chemical composition of the employed materials (% wt.). |
|---|---|---|---|---|---|---|---|
|   | Si  | Mn | Cr  | Mo  | V   | P   | Fe  |
| 1.2311 tool steel | 0.30 | 1.50 | 1.90 | 0.20 | -   | < 0.012 | Bal. |
| 1.2344 tool steel | 0.80 | 0.25 | 5.12 | 1.33 | 1.13 | 0.010 | Bal. |

Figure 1. (a) MI cables employed for the experimental testing, (b) schematic illustration of the structure of the MI cables, and (c) schematic illustration of the embedded MI cable.

2.2. Methods

A flow chart describing the methodology followed to perform the work is depicted in figure 2. Firstly, preliminary tests have been performed to characterise the L-DED powder and to obtain the optimised parameters for its deposition. Therefore, two sets of testing have been carried out:

- Geometric characterisation of 1.2344 tool steel over 1.2311 tool steel: optimum L-DED parameters have been obtained by means of Design of Experiments (DOE), where a Response
Surface Methodology (RSM) has been employed. Additionally, the adequate overlap has been determined.

- Study of the influence of the L-DED parameters in the dilution when depositing 1.2344 tool steel over 1.4401 stainless steel tubes: in order to minimise the dilution of the deposited material and, consequently, improve the survivability of the MI cables during the integration process, the feed rate and the powder rate have been gradually increased taking as reference the parameters obtained in step 1, and the resulting dilution has been measured.

![Figure 2. Diagram of the methodology followed during the study.](image)

Secondly, two strategies have been developed in an iterative manner to integrate the MI cables into the 1.2311 tool steel substrate, following the scheme showed in figure 1(c). There are two main issues to be faced when developing the strategy. On the one hand, the heat evacuation needs to be promoted, in order to avoid excessive temperatures in the surroundings of the MI cables. On the other hand, path programming in 5-axis is needed due to the geometry of the MI cables. Therefore, in the first strategy the following preventive measures have been set (figure 3):

- Clads have been deposited in an alternating manner in the right and left side of the cable, until the top of the MI cable is reached, and the component is enclosed. In this manner, heat accumulation is reduced.
- In order to reach the desired geometry as precisely as possible, the nozzle has been kept perpendicular to the substrate surface when possible, in fact, the position of the nozzle is limited by the possibility of collision.
- Waiting time between layers has been introduced to avoid the overheating of the substrate.

![Figure 3. Deposition strategy for the integration of the MI cables.](image)

After analysing the results obtained for the first strategy, a second one has been developed introducing new preventive measures to minimise the penetration of the laser in the first layers:

- The laser power has been reduced from 700 W to 500 W in the first two layers to reduce the heat input.
- A waiting time of 30 s between the deposition of successive clads has been introduced additionally to the previous waiting time, to reduce the overheating of the substrate.

Finally, in order to evaluate the integrity of the MI cables after the integration process, the continuity of the conductors has been checked. Also, three cross-sections of each sample have been analysed by confocal microscopy to assess the metallurgical integrity of the MI cables, the limits of the heat affected zones, and the geometry of the deposited clads. Therefore, the samples have been prepared following a
standard metallographic procedure and they have been chemically etched with Marble’s reagent.

3. Results and discussion

3.1. Preliminary tests
On the one hand, as far as the preliminary tests are concerned, defect-free and good-integrity clads are obtained with the parameters shown in table 2. Additionally, a 30% overlap has been found to give the best results.

| Power, P [W] | Feedrate, F [mm/min] | Mass powder rate, M [g/min] |
|--------------|-----------------------|-----------------------------|
| 700          | 450                   | 4.5                         |

On the other hand, and as far as the study of the dilution in DIN 1.2344 tool steel over tubular DIN1.4401 stainless steel is concerned, little influence of the studied parameters has been found when varying the federate in the range of 450 mm/min to 650 mm/min and the mass powder rate between 4.5 g/min and 6.5 g/min. In fact, dilution of approximately 0.2 mm has been obtained for all tests. Consequently, the parameters depicted in table 2 have been taken as reference for the MI cable integration tests.

3.2. MI cable integration tests: strategy 1
On the basis of previously carried out tests, the strategy explained in the methodology section has been applied to the 3, 4.5, 6.5, and 8 mm-diameter MI cables. In figure 4, the resulting samples are shown. Additionally, in table 3 a summary of the obtained results is presented. The deposition strategy was successful only in the integration of the 8 mm-diameter MI cable, as the heat evacuation issue is less restrictive in that case.

| MI cable Ø, mm | Continuity | Metallurgical integrity |
|----------------|------------|------------------------|
| 3              | Not measured | Poor      |
| 4.5            | Not OK     | Poor      |
| 6.5            | OK         | Poor      |
| 8              | OK         | Appropriate |

Figure 4. Embedded MI cables.

Figure 5. (a) Cross-section of the embedded 8 mm-diameter MI cable and details of critical areas, and (b) detected cracking in the upper zone of the coating.

3.2.1. Ø 8 mm MI cable. As aforementioned, the embedment of the component was successful. In figure 5(a) the cross-section of the sample is shown. Moreover, details of critical areas such as the joining between the external cover of the cable and the substrate, and the cover and the coating are shown. In both areas, a metallurgical bond has been obtained and, therefore, an appropriate heat transmission between the sensor and the tooling can be ensured. However, cracking and some lack-of-fusion defects
have been detected along the coating (figure 5(b)). Finally, as far as the continuity of the internal conductors is concerned, positive results have been obtained and a correct functionality of the cables assured.

3.2.2. Ø 6.5 mm MI cable. A partially successful embedment of this MI cable was also obtained following the first strategy. However, due to excessive heat input, the external cover was damaged. Nonetheless, the conductors remain unaffected and functional. As far as the defectology of the deposited material is concerned, several lack-of-fusion defects were found in the 1.2344 tool steel coating. Just as in the previous case, these are mostly located in overlapping areas and are due to an insufficient overlap.

![Image](a)

![Image](b)

*Figure 6. (a) Cross-section of the embedded 6.5 mm-diameter MI cable and details of critical areas, and (b) detected cracking in the upper zone of the coating.*

3.2.3. Ø 4.5 and Ø 3 mm MI cables. In the case of the smallest studied cables, the electronic components have been severely damaged during the L-DED process. In terms of metallurgical integrity, and on the basis of the metallographic analysis, it is quite evident that the external cover of the MI cables has been destroyed (figure 7). Additionally, during the continuity check it has become apparent that the functionality of the components has been completely jeopardized due to an excessive heat input as compared to the heat evacuation capacity.

Based on the obtained results for the first strategy, it is concluded that the heat input needs to be lowered at least in the first layers in order to reduce the processing temperatures. In this manner, the damage of the electronic components can be minimised. On the other hand, the deposition strategy needs to be revisited to avoid the lack-of-fusion defects in the coatings. To that end, as previously described in the methodology section, preventive measures have been introduced for the second strategy: (1) reducing the laser power in the first two layers and (2) introducing a waiting time between the deposition of successive clads.

3.3. MI cable integration tests: strategy 2

In this strategy, the laser power has been lowered from 700 W to 500 W in the first two layers and a 30 s wait between successive clads is introduced. In this manner, the heat input and the overheating of the substrate due to the L-DED process can be reduced.

![Image](a)

![Image](b)

*Figure 7. Cross-section of the embedded 4.5 and 3 mm-diameter MI cables.*

3.3.1. Ø 8 and Ø 6.5 mm MI cables. Owing to the reduced heat input, a successful integration of both diameter MI cables has been obtained by employing the second strategy (figure 8). In this case, the cover
of the 6.5 mm-diameter cable has not been perforated during the deposition process and good quality and high integrity coatings have been achieved (figure 8(b)). Furthermore, the continuity of the components remains unimpaired and, therefore, the cables have maintained their functionality.

3.3.2. Ø 4.5 and Ø 3 mm MI cables. Similar results as in the first strategy have been obtained when embedding the smallest diameter MI cables. The excessive heat input and the insufficient heat evacuation capacity resulted in high processing temperatures in the surroundings of the MI cables, leading to their destruction.

4. Conclusions

In this work a methodology suitable for embedding electronic components for temperature measurement devices into hot-stamping tooling has been developed. During this study, attempts to integrate 3, 4.5, 6.5, and 8 mm-diameter MI cables have been carried out. It has been concluded that the developed methodology is valid to integrate down to 6.5 mm-diameter MI cables by depositing 1.2344 tool steel coating onto the aforementioned cables and 1.2311 tool steel substrate. Smaller components prevent a correct heat evacuation during the L-DED process due to the small thickness of the external cover. This leads to unbearable processing temperatures, resulting in the destruction and complete loss of the functionality of the embedded component itself. Additionally, lack-of-fusion defects have been detected in the higher-diameter MI cables, owing to an insufficient overlap.

In order to further improve the strategy, some aspects can be revisited. Firstly, adaptive process parameters along the L-DED process could be incorporated. In this manner, the processing temperatures could be limited and the destruction of the components avoided, while ensuring a correct bonding between the embedded component and the tooling. Secondly, lack-of-fusion defects need to be addressed. To that end, the deposition path needs to be optimised and the overlap recalculated.

To sum up, a preliminary attempt to fabricate smart tooling for metal forming processes has been carried out during this work. The development of a methodology for embedding temperature measurement devices into tooling significantly contributes to the integration of sensing technologies in the die and mould sector, taking a step forward towards the realisation of smart factories and the implementation of Industry 4.0.

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