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METHODOLOGY FOR CREATING A SOFTWARE FOR STRUCTURING THE RECONSTRUCTION TECHNOLOGIES BY LASER WELDING OF METAL MOULDS

BY

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Abstract. Metal and plastic parts are made in moulds, in production processes such as plastic injection, metal alloy die casting and metal deformation. During operations, moulds are exposed to severe conditions: wear, impact, corrosion, thermal cycling and high mechanical stresses. Moulds reconstruction has advanced, precisely because to new technologies, such as laser welding. Laser technologies offers several benefits, including increase of work speeds, reduced thermally influenced zones and material losses and decreased additional working times for mechanical machining processes.

Keywords: laser welding, mould reconstruction, software.

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1. Introduction

Almost all mass-produced metal and plastic parts are made in metal moulds, in production processes such as plastic injection, metal alloy die casting and plastic deformation moulding. To enhance economic efficiency, it is crucial to maintain moulds in a well-functioning state, thereby extending their lifespan beyond the usual constraints imposed by wear, accidental damage, or obsolescence. Moulds endure harsh operating conditions when in use, including impact, thermal cycling, continuous wear, corrosion, and high mechanical stresses. These conditions subject the molds to constant damage (Changrong *et al.*, 2014).

Moulds reconstruction has developed more and more, precisely because to new repair techniques and technologies, such as laser beam welding. By using laser technologies, the benefits are maximum and the main advantages are observed in the increase of work speeds, the reduction of thermally influenced zones (Heat Affected Zones), reductions of material losses, the decrease of additional working times for other mechanical machining processes, heat treatments, grinding.

The laser mold repair welding technologies can quickly and accurately repair the cracks, pores, wear defects, slag holes, chippings, edges, corners and shrinkage holes formed during the operating processes of the moulds. The main reasons for choosing laser welding technologies for the reconstruction of metal moulds are those that bring the greatest benefits, both technically and economically:

- Limited heat-affected zone (HAZ) and very small thermal deformation (very suitable for processing materials with high melting point, high hardness, and unique materials);
- No modifications in the microstructure of the base materials or filler material (welding wire);
- On regular parts, as well on parts with intricate shapes or small sizes can be made a heat treatment (partially);
- Notably, there is no requirement for preheat treatment and the workpiece will not undergo annealing after welding; Additionally, when there operation is made with the same material as base material, it is very possible to achieve identical hardness;
- Laser welding proves versatile in working with a wide range of metal grades and types as: titanium, alloyed steels, nickel, aluminium, high alloyed steels, tin, zinc, copper, gold, chromium, silver, niobium, and other metals and their alloys. Furthermore, it is feasible to weld similar alloys such titanium-copper, nickel-copper, titanium-nickel and brass-copper;
- Lastly, laser welding alloys for the welding of dissimilar metals, such as carbon steel - copper and other heterogeneous metal combinations

(<https://us.hanslaser.net/products/laser-mold-repair-welding-machine-mold-301-302.html>).

2. The necessity to reconstruction of metal moulds

The global market for metal moulds worldwide is estimated at over \$200 billion. The high cost of the moulds due to very expensive materials and higher manufacturing precision makes the rapid rebuild mechanism an economically viable solution (Rao, 2012). This has encouraged the development of various techniques to repair and rebuild molds.

The following are some of the main types of metal moulds widely used in industry for obtaining finished products Fig. 1 - Glass; Fig 2 and Fig. 3 - Plastic parts; Fig. 4 - Metal elements.

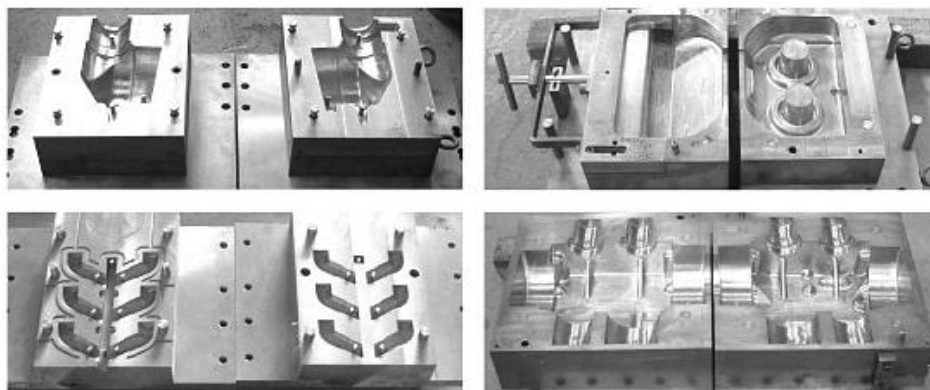


Fig. 1 – Metal moulds for forming glass objects.

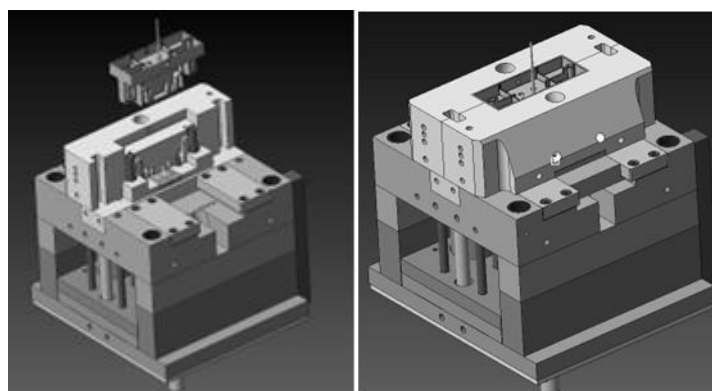


Fig. 2 – Plastic parts.

Fig. 3 – Plastic parts.

(www.meusbarger.com)

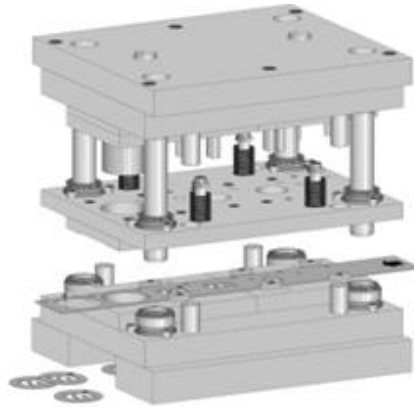


Fig. 4 – Metal elements (www.meusburger.com).

Faulty design is one of the important aspects that lead to the total failure of metal moulds. This irreversible damage can be avoided by the correct realization of sharp corners, notches and areas with sudden change in cross-section, which can lead to increased contact pressure and adversely affect the fatigue and wear behavior of the mould surface (Moura *et al.*, 2007). The use of softwares and computer-aided design can ensure the best solutions in the design of these tools.

Manufacturing failures occur due to non-conformity of specified materials and their manufacturing process. Although the purchased material was according to the desired specification, defects during the machining processes also caused the moulds to fail.

The implementation of post-machining heat treatment and additional finishing processes, such as electrical discharge machining and surface grinding holds significant importance due to the susceptibility of mould steel to cracking during these operations. Inadequate heat treatment can result in decreased hardness and diminished fatigue strength. Moreover, absence of lubrication during grinding process and improper grinding, in particular, can also lead to the formation of microcracks that extend over a broader surface area (Jhavar *et al.*, 2013).

The primary reasons for mold damage during operation stem from problems that arise in their applications. The failure mechanisms, such as hot working, mechanical fatigue, wear, or plastic deformation, are directly linked to the specific purposes they serve, namely hot working, cold working, and the manufacturing of plastic deformable parts.

Molds used in hot working applications are particularly susceptible to issues like cracking, thermal fatigue, plastic deformation, and corrosion. This vulnerability is attributed to the repetitive heating and cooling cycles they undergo in addition to the general mechanical loading they endure.

On the other side, molds utilized in cold working face failure mainly due to loading impact and the initiation of cracks from material fatigue in areas where stress concentration occurs (Alaneme *et al.*, 2009).

Mould wear is the most obvious and influential phenomenon and occurs as a result of interactions between two or more surfaces. These contacts cause deformation and damage of metal elements at the surface due to mechanical action and stresses developed subsequently. The behavior of metal molds is influenced by a combination of diverse factors, including complex geometry, the quality of the mold/plate, insufficient heat treatment, surface impurities, working environment conditions, as well as pressure and temperature variations.

According to the literature and statistics from industrial field it is estimated that over 80% of the moulds used for the production of automotive components are subject to a rebuilding/repair process.

3. Types of the moulds defects

The materials used in metal moulds are prone to developing numerous cracks as a result of thermal fatigue caused by the cyclic heating and cooling they undergo. The repetitive cycles of heating and cooling generate a temperature gradient within the molds, leading to the accumulation of thermal stresses in adjacent layers. These thermal stresses significantly contribute to the formation and propagation of surface cracks (Jhavar *et al.*, 2013). As cracks increase in depth, the effect of thermal cycling decreases, the material invariably stops the propagation of these cracks into the interior of the moulds. Consequently, a significant multitude of tiny cracks emerge on the surface of the mold, characterized by shallow depth, resulting from temperature fluctuations. Researchers have documented that in scenarios where larger local stresses align with other global stresses during operation, these cracks tend to exhibit greater depth (Jhavar *et al.*, 2013).

The Fig. 5 shows the erosion wear patterns and cracks of defects that can occur in various mould components as a result of use during production processes.

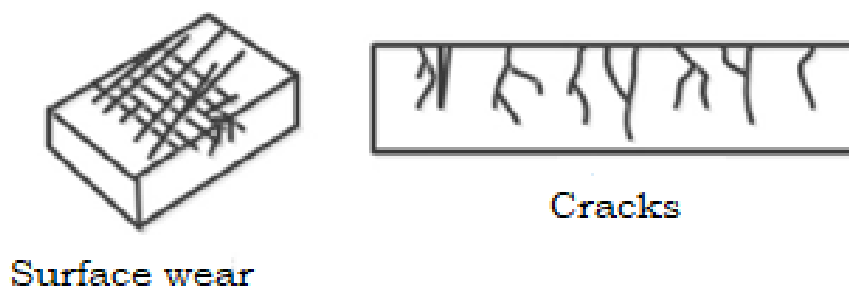


Fig. 5 – Typical defects (Wang and Yang, 2008).

The Fig. 6 shows the defects that can occur in various mould components for ductile and brittle materials respectively (Wang and Yang., 2008).

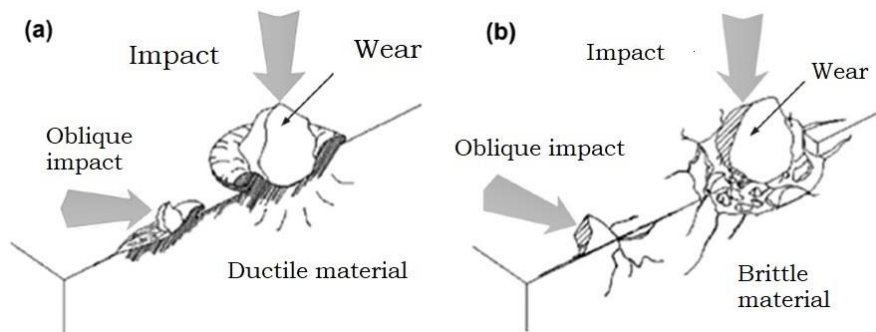


Fig. 6 – Typical defects (Wang and Yang, 2008).

The Fig. 7 shows multiple types of defects caused by plastic deformation, wear an thermal cycling (Tusek *et al.*, 2007).

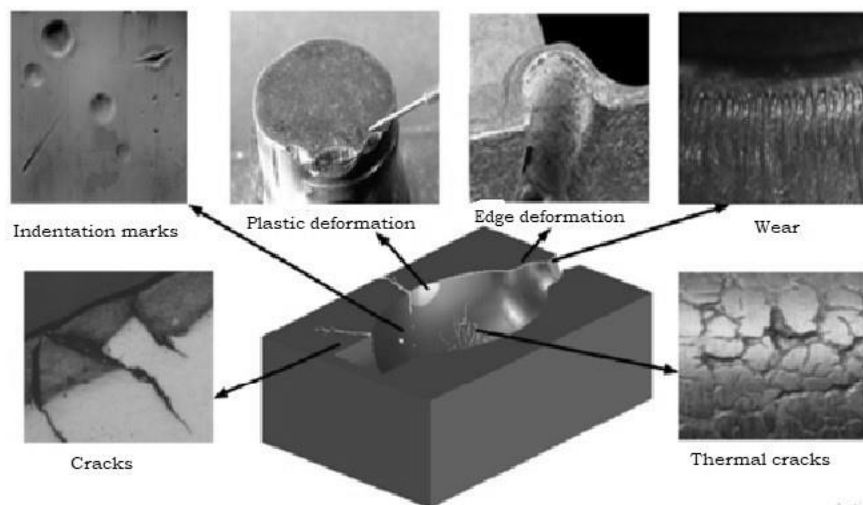


Fig. 7 – Multiple types of mould defects (Tusek *et al.*, 2007).

4. Reconstruction of metal moulds by laser welding

The timeliness of the experimental research undertaken resulted from the numerous experimental observations that showed that the rebuilding/modification/repair of metal moulds is a much less expensive solution, first of all, compared to the total replacement by producing a new mould, with multiple advantages regarding the greening of industrial production processes.

In practice, the use of metal mould rebuilding has been a successful technique for many years and the recent involvement of laser welding equipment in this process brings many advantages in all aspects - technical, economic, ergonomic and environmental - to the development of this segment of production systems.

The reconstruction of moulds can be improved by using laser technologies and the main benefits can be seen in: increased working speed, reduction of thermally influenced areas, reductions in material losses, considerably reduced mechanical machining dimensions. The lifetime of industrial moulds can be improved by timely repair of damaged surfaces.

The degree and severity of damage to these essential production tools depends on the service conditions and form tolerances that must be respected at the end and the dimensions of the moulds.

The subject matter is multidisciplinary in nature, requiring a broad knowledge of mechanical and materials engineering, physics, chemistry and experimental analysis, allowing contributions in all areas of special metallic materials, laser processing technologies and actual applications of the finished products represented by the moulds.

When applying laser beam machining, the characteristics of the laser source - semifinished material-defect combination must be taken into account, as follows:

- type of laser source depending on the nature of the active medium;
- laser beam emission form: continuous or pulsed;
- wavelength of radiation;
- degree of absorption of the surface of the material to be processed;
- roughness of the initial surface;
- thermal properties of the workpiece material.

Thus, the main problem in establishing a laser beam machining technology is to find a balance between the energy transmitted by the laser beam and the energy required to vaporize the materials, since their machinability with laser beam differs depending on their composition (Birger *et al.* 2011; Capello *et al.*, 2005).

LASER - Light Amplification by Stimulated Emission of Radiation

- ❖ The required energy for melting is obtained by focusing the laser beam onto the separating surface of the two materials to be welded using optical lenses.
- ❖ Laser welding is carried out under an inert gas blanket, with or without using the filler material.
- ❖ Laser welding is carried out by fusion of the materials.

The deposition of the material is much more precise and easier to achieve:

- very small thickness

- starting from tens of microns
- slightest or without changes in the composition of the base material

The Fig. 8 illustrate the laser welding process, focused and explained the thermal convection and conductivity of the energy in the base material.

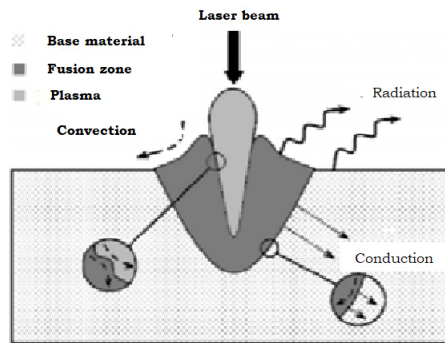


Fig. 8 – Laser welding process (Leunda *et al.*, 2011).

The introduction of Nd:YAG crystal lasers and high-power fibre lasers in the market has brought about significant reductions in operating and maintenance costs. This development has changed the approaching of laser-based material deposition. When we take in consideration to adding material, two common methods are used: powder or wire. In the industry, wire feed is preferred for continuous deposition of components because intermittent start and stop of the material flow can disrupt the deposited material. With wire feeding, the wire is in constant contact with the melt pool on the substrate. However, any inaccuracies in wire positioning or feed speed can affect the shape and size of the melt pool (www.ila.org.in).

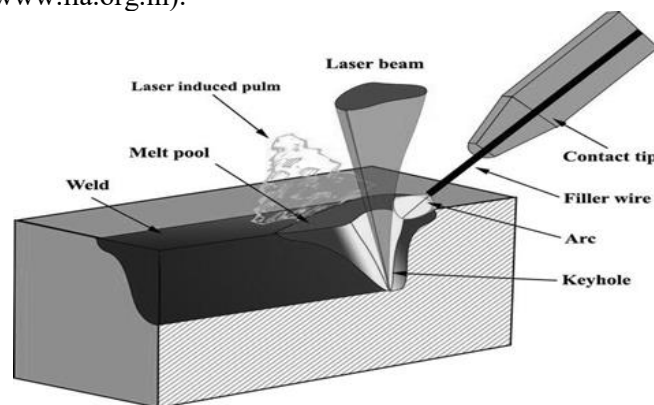


Fig. 9 – Laser welding process
(<https://alphalaser.eu/en/industries/toolmaking-molding.html>).

As a result of this disruption, the deposited materials or parts exhibit a non-uniform or asymmetrical shape. Additionally, achieving high-quality deposition requires adhering to a well-established ratio of beam diameter to wire diameter. In this context, high-quality deposition refers to the ability of the deposited material to form a strong bond with the substrate and for the fed material to spread evenly during the deposition process, resulting in a uniform and smooth surface. The properly size of the wire and a very precise positioning of it on the substrate are crucial factors in laser welding using wire feeders (Fig. 9).

In contrast, powder feeding offers significant advantages, primarily attributed to its precise control and flexibility during material cladding (www.ila.org.in).

5. The methodology for creating a software for structuring the reconstruction technologies by laser welding of metal moulds

A correct, efficient and optimized laser welding process must have a number of parameters that the operator will enter when setting up the equipment and choosing the best operating solution.

Based on the initial known information (Table 1) on types of the moulds, materials used for moulds, mechanical and material specifications (hardness, heat treatment), reconstruction equipments and desired characteristics following the process, the operator must set up the entire laser welding process such as filler material (welding wire), type of seam, technological parameters: maximum voltage (V), laser power (W), pulse energy (J), welding speed (mm/s), laser frequency (Hz), pulse duration (ms), laser beam diameter (mm), welding wire diameter (mm), welding wire tilt angle ($^{\circ}$), welding shielding gas, shielding gas flow rate (l/min) – Table 2.

Identifying an optimal welding regime involves setting the working parameters (energy density, speed of relative displacement between spot and blank or interaction time, etc.) so that the temperature in the welding zone is higher than the melting temperature but lower than the vaporisation temperature of the blank materials.

To set the process parameters, the laser pulse parameter settings must be taken into account. A few examples of these setting are presented following: the higher the voltage and the smaller the diameter, the more aggressive the laser beam (splashing, uncontrollable melting and no process safety!). The longer the pulse duration and the higher the frequency, the greater the thermal effects (diversity of annealing colours and thermal loading of the material). Consider the location to be welded, what characteristics the seam should have after welding after processing and very important is what filler material is suitable. Determine the nature of the base material (properties, thickness), parameters that are important for determining the pulse duration and frequency. Determine the size of the weld location which is important for selecting the diameter of the filler

material. Apply the following: wire diameter $\times 2 (+ 0.1) =$ laser beam focus diameter (<https://alphalaser.eu/en/industries/toolmaking-molding.html>).

Materials with low absorption and good heat conduction behaviour lead to an unsuitable melting background “e.g.” copper, gold or silver, on the other hand materials with high absorption and poor heat conduction behaviour give a good melting background “e.g.” titanium or iron alloys, here the melting temperature does not play an important role. For a durable and reproducible weld without filler material, the following guidelines should be observed: if possible, for elements with variable material thicknesses, weld at staggered heights, avoid excessively large gaps between the joint elements and due to the small laser beam diameter of 0.2 mm to 2 mm, seam preparation is important, especially when working with sheets.

Table 1
Presentation of the input data

Primary information	Description and examples
Types of the moulds	❖ Plastic injection moulds ❖ Plastic deformation moulding ❖ Metal alloy die casting
Materials used for moulds (grades) ➤ Steels ➤ Chrome-nickel alloys ➤ Nickel-based alloys ➤ Copper alloys ➤ Aluminium alloys ➤ Titanium ➤ And others	❖ Ex: DIN - 1.2343 / 1.730 / 1.2311 / 1.2344 / 1.2379 / 1.2767 / 1.2085 / 1.2080 / 1.2714HH / 1.3547 / 1.4009 / 2.4806 / 2.4856 / 2.1367
Hardness of the base material (Yes/No)	❖ HRC grade;
Heat treatment of the base material	❖ Ex: Hardened / Nitrided / DLC cover
Reconstruction equipments (Laser welding machine type)	❖ Nd:YAG laser; Fiber Laser
Desired characteristics following the process	❖ Mirror finish / Hardening / DLC Covering

Welding errors mainly result from: incorrect gas settings, “i.e” too little/no shielding gas at the weld site or incorrectly set pulse parameters, “i.e” too little/too much energy (= heat) at the weld site.

Currently, the parameters of the laser welding process, as well as of the welding equipment, are configured by the operator based on previous experience as well as on the recommendations of specialists from equipment manufacturers.

However, even for skilled operators, but especially for beginners, the process is a difficult, time-consuming, knowledge-intensive and resource-intensive one.

The software that will be created on the basis of this methodology presented in this paper, will provide (Table 2) to any operator, beginner or experienced, the certainty of configuring a set of parameters that will result in a correct, efficient and optimized laser welding process.

Table 2
Presentation of the output data

Information	Description
Filler material (welding wire)	Type of the welding wire fitted for the process
Type of seam	Single layer / Multi-layer
Technological Parameters	
Maximum voltage (V)	Maximum voltage allowed for this operation
Pulse energy (J)	Energy of the laser (calculated)
Laser frequency (Hz)	Frequency of the laser pulses
Laser beam diameter (mm)	Diameter of the laser beam (calculated = max 2 x wire Ø)
Laser power (W)	Power of the laser (calculated)
Welding speed (mm/s)	Advance speed of the welding process
Pulse duration (ms)	Duration of the laser pulse
Welding wire diameter (Ø)	Diameter of the welding wire required in the process
Welding wire tilt angle (°)	Angle of the wire used in the process (depending of the process)
Welding shielding gas	Ex: Argon / Nytrogen
Shielding gas flow rate (l/min)	Flow rate of shielding gas (depending of the welded material)

The methodology for the structuring of reconstruction technologies by laser welding requires the introduction all inputs data necessary in the reconstruction process to achieve a correct, automated and optimized laser welding process.

INPUT DATA			OUTPUT DATA	
Types of the moulds			Filler material (welding wire)	
Materials used for moulds			Type of seam	
			Maximum voltage (V)	
			Pulse energy (J)	
Hardness of the base material		 SOFTWARE	Laser frequency (Hz)	
Heat treatment of the base material			Laser beam diameter (mm)	
			Welding wire tilt angle (°)	
Reconstruction equipments			Laser power (W)	
Desired characteristics following the process			Welding speed (mm/s)	
		Pulse duration (ms)		
		Welding wire diameter (mm)		
		Welding shielding gas (type)		
		Shielding gas flow rate (l/min.)		

Fig. 10 – Computer process diagram.

The software that will be created based on this methodology will be built in the Python 3.10 programming language, and the software interface will be designed and created using the TK Inter library also in the Python 3.10 programming language.

6. Conclusions

The methodology for creating a software for structuring the reconstruction technologies by laser welding:

- Consists of a series of activities identified on the basis of the need to rebuild metal moulds used in mass production;
- Requires the inputs of all necessary data in the reconstruction process, as well as desirable characteristics;
- Based on the input information and on the relations between them (written in the software), will be provided Output data for technological process;
- From Output data, the operator of the welding laser machine will achieve a correct, automated and optimized laser welding process.

The software created based on this methodology for structuring the reconstruction technologies by laser welding of the metal moulds will provide:

- ❖ A powerful instrument for the entire process of reconstruction;
- ❖ Time saving to achieve, rather than repeated trials, the maximum efficiency parameters;
- ❖ Resources saving: materials, time, energy, environmental safety;
- ❖ For inexperienced as well as experienced users, a real support to learn and consolidate the knowledge of laser welding reconstruction technologies of metal moulds.

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REFERENCES

- Alaneme K.K., Adewuyi B.O., Ofoegbu F.A., *Failure analysis of mould dies of an industrial punching machine*. Eng Fail Anal 2009, 16, 2043–2046.
- Birger E.M., Moskvitin G.V., Polyakov A.N., Arkhipov V.E., *Industrial laser cladding: current state and future*, In: Welding International, Vol. 25, No. 3 (2011), 234–243.
- Capello E., Colombo D., Previtali B., *Repairing of sintered tools using laser cladding by wire*, In: J. Mater. Process. Technol., 164–165 (2005), 990–1000.
- Changrong Chen, Yan Wang, Hengan Ou, Yan He, Xianzhi Tang, *A review on remanufacture of dies and moulds*, Journal of Cleaner Production, 2014.

- Jhavar S., Paul C.P., Jain N.K., *Causes of failure and repairing options for dies and molds: A review*, Engineering Failure Analysis, 2013.
- Leunda J., Soriano C., Sanz C., Garcia Navas V., *Laser Cladding of Vanadium-Carbide Tool Steels for Die Repair*, In: Physics Procedia, 12 (2011), 345-352.
- Moura G.C.R., Aguilar M.T.P., Pertence A.E.M., Cetlin P.R., *The materials and the design of the die in a critical manufacturing step of an automotive shock-absorber cap*. Mater Des. 2007, 28, 962–968.
- Rao Indira, *Casting dies for a sustainable future*, EM; May–June 2012.
- Tušek J., Taljat B., Klobčar Damjan, *How to Extend the Life of Die-Casting Tools*. Metalurgija. 46 (2007).
- Wang Y.F., Yang Z.G., *Finite element model of erosive wear on ductile and brittle materials*, Wear 2008, 256, 871-878.
- <https://alphalaser.eu/en/industries/toolmaking-molding.html> (accessed on 13.06.2023).
- <https://meusburger.com> (accessed on 13.06.2023).
- <https://us.hanslaser.net/products/laser-mold-repair-welding-machine-mold-301-302.html> (accessed on 14.06.2023).
- www.ila.org.in (accessed on 11.05.2023).

METODOLOGIE DE REALIZARE A UNUI PROGRAM INFORMATIC
PENTRU STRUCTURAREA TEHNOLOGIILOR DE RECONSTRUCȚIE PRIN
SUDAREA CU LASER A MATRIȚELOR METALICE

(Rezumat)

Piese din metal și plastic sunt realizate în matrițe, în procese de producție precum injecția de plastic, turnarea sub presiune a aliajelor metalice și deformarea metalelor. În timpul operațiunilor, matrițele sunt expuse la condiții severe: uzură, impact, coroziune, cicluri termice și tensiuni mecanice ridicate. Reconstrucția matrițelor a avansat, tocmai datorită noilor tehnologii, cum ar fi sudarea cu laser. Tehnologiile laser oferă mai multe beneficii, printre care creșterea vitezelor de lucru, reducerea zonelor influențate termic și a pierderilor de material și scăderea timpilor de lucru suplimentari pentru procesele de prelucrare mecanică.