DEVELOPMENT OF A HYBRID MACHINE (MACHINING-LMD) AND ITS APPLICATION FOR THE MANUFACTURING OF RUBBER EXTRUSION SCREWS

A. Olaiz, N. Lety, A. Alberdi, M. Ortiz, P. Ramiro, A. Lamikiz, I. Arrizubieta, E. Ukar, G. Chambon
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Background
State of the art on hybrid machines

- OKUMA Laser EX SERIES
  - LMD+Multitaks + Grinding + heat treatment

- MAZAK Integrex i AM series
  - LMD + Multitask

- MAZAK Integrex i-400 AM
  - LMD + Multitask

- DMG-MORI LASERTEC 65 3D:
  - LMD+ Milling

- HERMLE
  - C-40 type 5-axis machining center
    - MPA (Metal Powder Application) Technology + Milling

- MATSUURA
  - Lumex Avance-25
    - SLM+ Machining

- WFL MILLTURN
  - LMD+ Machining

- OKUMA
  - Laser EX SERIES
  - LMD+Multitaks + Grinding + heat treatment
Background

ZVH 45/1600 Add & Process

- Cooling system from Lotek
- LMD Head YC52 Precitec 4 stream
- Head switching arm
- Security and enclosure system
- Optical fiber 400µm
- Laser ROFIN FL 030 3kW fibre-Yb
- Powder feeder Sulzer Metco TWIN-10-C
BACKGROUND
PARADDISE project

A Productive, Affordable and Reliable solution for large scale manufacturing of metallic components by combining laser-based ADDitive and Subtractive processes with high Efficiency

www.paraddise.eu

OBJECTIVE

To rationalize, to structure and to make available the tools for combining two antithetical processes: Laser Metal Deposition (LMD) and Machining (milling and turning)

- START DATE: 1st October 2016
- DURATION: 36 months
- Coordinator: Tecnalia Research & Innovation
- Budget: 3,761,403€
BACKGROUND

Michelin use case

- Michelin produces **200 screws/year** for using in their rubber extruders for the tire production

  ![Rubber extruder diagram]

  - Filets of screws subjected to **high temperatures** and **high friction**

- Michelin has installed his third Ibarmia's machine in December 2016 with basic equipment
- This “multiprocess” machine work today in milling mode exclusively
Objetives of the work

1st OBJECTIVE

To make an experimental analysis of LMD process for extrusion screws in order to increase their lifetime by adding high resistant coatings in new filets and by repairing the worn screws before being discarded.

COATING REQUIREMENTS

- **Hardness**: equal to the minimum given by the powder suppliers on the technical data
- **Layer height** > 0.5 mm
- **MDR** (Material Deposition Rate) > 0.5 kg/h (similar to TIG process)
- **Powder efficiency**: 90%
- The surface after coating must be homogeneous. Ra <0.8µm after grinding.

- **Material**: 42CrMoS4
- **Ø** = 40-350 mm
- **Length** up to 5m
Objetives of the work

2nd OBJECTIVE

To set up the machine available at Michelin facilities for the LMD technology

- Development of cleaning systems: chip & powder removal
- Chemical hygiene requirements
- To avoid laser reflections

3rd OBJECTIVE

To develop a CAD/CAM/CAE solution for hybrid (LMD-machining) manufacturing
LMD Process
Approach: Materials

BASE MATERIAL: Structural Steel 42CrMoS4
✓ Moderate to high loads
✓ Hot working conditions (up to 500ºC)
× Low weldability: high risk for cracks ➔ preheating recommended

- Equivalent Carbon (International Institute of Welding):

\[
C_{eq} = C + \frac{Mn}{6} + \frac{(Cr+Mo+V)}{5} + \frac{(Cu+Ni)}{15} = 0.767\% \quad >0.43\% \quad ➔ \text{preheating needed}
\]

- Séférian Method:

\[
T_p \text{[°C]} = 350 \cdot \sqrt{(1 + 0.005 \cdot e) \cdot C_q - 0.25} = 257°
\]

BASE MATERIAL CONDITIONS:
1) NO preheating & NO heat treatment ➔ 33HRC
2) NO preheating & WITH hardening heat treatment: 850ºC heating in oven during 2.5h, cooling in oil, heating to 250ºC during 2.5h and cooling in air ➔ 52HRC
3) WITH preheating & NO heat treatment ➔ 32 HRC
LMD Process
Approach: Materials

COATING Powder
- Base Fe: EUTROLOY 16606A.04
- Base Co: EUTROLOY 16006N (Equivalent to Stellite 6)
- Base Ni: COLMONOY 56 PTA

<table>
<thead>
<tr>
<th>Shape</th>
<th>Eutroloy 16606</th>
<th>Stellite 6</th>
<th>Colmonoy 56</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size [µm]</td>
<td>d_{50} (d_{90} - d_{50}; d_{50} - d_{10})</td>
<td>113 (+49;-40)</td>
<td>90 (+43;-33)</td>
</tr>
<tr>
<td>Fluidity [s/50g]</td>
<td>11.9</td>
<td>10.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Density, ρ [g/cm³]</td>
<td>7.9</td>
<td>8.44</td>
<td>8.18</td>
</tr>
</tbody>
</table>

Eutroloy 16606  Stellite 6  Colmonoy 56
**LMD Process**

**Approach: Experimental procedure**

**STEP 1:** To find **optimum LMD parameters:** manufacturing of **simple clads**

**Design of Experiments: Factors and levels**

<table>
<thead>
<tr>
<th>P [W]</th>
<th>N_{polvo}</th>
<th>v_f [mm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>50%</td>
<td>750</td>
</tr>
<tr>
<td>2000</td>
<td>75%</td>
<td>1000</td>
</tr>
<tr>
<td>2500</td>
<td>100%</td>
<td>1250</td>
</tr>
</tbody>
</table>

**EVALUATION CRITERIA**

- Height (H) and Width (W)
- Dilution \( d = \frac{b}{b+H} \)
- Material Deposition Rate \( MDR = \frac{A \cdot v_f \cdot \rho}{\text{number of layers}} \)
- Powder Efficiency \( \epsilon = \frac{MDR}{\dot{m}_p} \)
- Structural integrity
**LMD Process**

**Approach: Experimental procedure**

**STEP 2:** To manufacture coatings *overlapping single clads* by using 3 optimum process parameters selected in step 1

**EVALUATION CRITERIA**

- Layer Height, $H$
- Material Deposition Rate $\frac{A \cdot v_f \cdot \rho}{\# \text{layers}}$
- Powder Efficiency $\varepsilon = \frac{MDR}{\dot{m}_p}$
- Productivity [mm$^2$/min] $Pr = (1-\text{overlap}) \cdot W \cdot v_f$
- Structural integrity
- Hardness profile
LMD Process
Approach: experimental procedure

STEP 3: **Pin on Disk wear testing** in coated samples with optimum process parameters for each material and in a reference sample (base-material)

![Diagram of pin on disk wear testing apparatus](image)

### Pin on disk wear Test conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Unit</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>N</td>
<td>5</td>
</tr>
<tr>
<td>Velocity</td>
<td>cm/s</td>
<td>20</td>
</tr>
<tr>
<td>Test radius</td>
<td>mm</td>
<td>18</td>
</tr>
<tr>
<td>Rotation</td>
<td>rpm</td>
<td>106.1</td>
</tr>
<tr>
<td>Test duration</td>
<td>min</td>
<td>30</td>
</tr>
<tr>
<td>Test temperature</td>
<td>°C</td>
<td>100</td>
</tr>
<tr>
<td>Pin material</td>
<td>-</td>
<td>AISI 52100 (HRc 62-66)</td>
</tr>
<tr>
<td>Pin diameter</td>
<td>mm</td>
<td>Ø 6</td>
</tr>
</tbody>
</table>

**Samples coated by LMD + ground**
LMD Process
Results: Height, MDR, efficiency and productivity

<table>
<thead>
<tr>
<th>Material</th>
<th>$\dot{m}_p$ [g/min]</th>
<th>P [W]</th>
<th>$v_f$ [mm/min]</th>
<th>H [mm]</th>
<th>d [%]</th>
<th>MDR [kg/h]</th>
<th>ε [%]</th>
<th>Productivity [mm²/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NO preheating WITH heat treatment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eutroloy 16606</td>
<td>21.97 (50%)</td>
<td>2500</td>
<td>1250</td>
<td>0,76</td>
<td>34,85</td>
<td>0,57</td>
<td>43,49</td>
<td>1581,25</td>
</tr>
<tr>
<td>Stellite 6</td>
<td>21.17 (50%)</td>
<td>2500</td>
<td>1250</td>
<td>0,85</td>
<td>9,62</td>
<td>0,72</td>
<td>56,64</td>
<td>1662,50</td>
</tr>
<tr>
<td>Colmonoy 56</td>
<td>17.6 (50%)</td>
<td>2500</td>
<td>1250</td>
<td>0,78</td>
<td>28,33</td>
<td>0,75</td>
<td>70,86</td>
<td>1950,00</td>
</tr>
<tr>
<td><strong>NO preheating NO heat treatment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eutroloy 16606</td>
<td>21.97 (50%)</td>
<td>2500</td>
<td>750</td>
<td>0,92</td>
<td>30,77</td>
<td>0,48</td>
<td>36,22</td>
<td>1091,25</td>
</tr>
<tr>
<td>Stellite 6</td>
<td>21.17 (50%)</td>
<td>2500</td>
<td>1250</td>
<td>0,68</td>
<td>38,93</td>
<td>0,58</td>
<td>45,32</td>
<td>1662,50</td>
</tr>
<tr>
<td>Colmonoy 56</td>
<td>17.6 (50%)</td>
<td>2000</td>
<td>1250</td>
<td>0,74</td>
<td>16,51</td>
<td>0,51</td>
<td>48,25</td>
<td>1412,50</td>
</tr>
<tr>
<td><strong>WITH preheating NO heat treatment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eutroloy 16606</td>
<td>21.97 (50%)</td>
<td>2500</td>
<td>1250</td>
<td>0,76</td>
<td>41,36</td>
<td>0,57</td>
<td>42,96</td>
<td>1581,25</td>
</tr>
<tr>
<td>Stellite 6</td>
<td>21.17 (50%)</td>
<td>2500</td>
<td>1250</td>
<td>0,84</td>
<td>19,16</td>
<td>0,71</td>
<td>55,94</td>
<td>1662,50</td>
</tr>
<tr>
<td>Colmonoy 56</td>
<td>17.6 (50%)</td>
<td>2000</td>
<td>750</td>
<td>1,18</td>
<td>22,1</td>
<td>0,65</td>
<td>61,59</td>
<td>1125,00</td>
</tr>
</tbody>
</table>
LMD Process
Results: Structural integrity

<table>
<thead>
<tr>
<th>Material</th>
<th>No Preheating</th>
<th>Heat Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUTOLOY 16606</td>
<td>No</td>
<td>With</td>
</tr>
<tr>
<td>STELLITE 6</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>COLMONOY 56</td>
<td>With</td>
<td>No</td>
</tr>
</tbody>
</table>

Porosity:
- EUTOLOY 16606: OK
- STELLITE 6: OK
- COLMONOY 56: POROSITY
LMD Process
Results: Hardness profile

![Graph showing hardness profile with preheating and heat treatment variations.](graph.png)
## LMD Process

### Results: Pin on Disk

<table>
<thead>
<tr>
<th>Sample</th>
<th>Wear track [mm³/(N•m)]</th>
<th>Wear pin [mm³/(N•m)]</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>42CrMoS4-REF</td>
<td>-</td>
<td>5.42E-05</td>
<td>0.84</td>
</tr>
<tr>
<td>Eutroloy 16606</td>
<td>-</td>
<td>8.15E-05</td>
<td>0.91</td>
</tr>
<tr>
<td>Stellite 6</td>
<td>3.38E-04</td>
<td>1.70E-06</td>
<td>0.54</td>
</tr>
<tr>
<td>Colmonoy 56</td>
<td>4.08E-04</td>
<td>1.01E-05</td>
<td>0.60</td>
</tr>
</tbody>
</table>

**Eutroloy 16606**

**Stellite 6**

**Colmonoy 56**

Due to intermetallic compound formation

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**Hardness HRC**

- **Eutroloy 16606**
- **Stellite 6**
- **Colmonoy 56**

- Hardened
- Pin on disk
Machine Set-Up
Cleaning systems: Chip & Powder removal

Cleaning systems in the **front** of the machine and in **both lateral sides** of the table.

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**Special tool design** for powder removal:
- stored in the ATC
- the coolant goes directly through the electrospindle
- maximum flow: 40 l/min

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**Drag link type chip conveyor**

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**Air aspiration:**
- Filter Hepa H13 (filtration grade 99.95%)
Machine Set-Up
Chemical Hygiene

Methodology specified in the MTA *(Methods of Sampling and Analysis)* normative of INSHT *(National Institute of Safety and Hygiene at Work)* and NIOSH *(National Institute for Occupational Safety and Health)*

- **Evaluation criteria:**
  - Real Decreto 374/2001 de 6 de abril sobre la protección de la salud y seguridad de los trabajadores contra los riesgos relacionados con los agentes químicos durante el trabajo.
  - Norma UNE-EN 689:1996. atmósferas en el lugar de trabajo. Directrices para la evaluación de la exposición por inhalación de agentes químicos para la comparación con los valores límite y estrategia de medición.

- **Measurements done in Tecnalia:**
  - **3 type of powder materials:** Eutroloy 16606, Stellite 6 and Colmonoy 56
  - Analyzed processes: powder **handling, LMD process and cleaning** with hoover

**RESULTS**

- **ACCEPTABLE** exposure values: I (Occupational Exposure Index)<0.1
- All values fulfill Michelin requirements
- Periodic measurements recommended every 64 weeks
Machine Set Up
Laser reflections

Reflection measurements done in TECNALIA, according to:

- EN 60825-1:2014 Seguridad de los productos láser. Parte 1: Clasificación de los equipos y requisitos
- EN 60825-4:2006 Seguridad de los productos láser. Parte 4: Sistemas de protección frente a la radiación láser
- EN 297-2009 Equipo de protección individual de los ojos. Óculos e proteções de olhos contra radiação láser (gafas de protección láser)
- Directiva 2006/25/CE del Parlamento Europeo y del Consejo, de 5 de abril de 2006, sobre las disposiciones mínimas de seguridad y de salud relativas a la exposición de los trabajadores a riesgos derivados de las agentes físicos (radiaciones ópticas artificiales)

RESULTS

The machine is a **CLASS 1 LASER SYSTEM**: People outside the enclosure should not use PPEs they will be protected by collective protection measures.

However, full enclosure of the machine is being designed.
Conclusions

- It is possible to manufacture high resistant coatings based on Eutroloy 16606, Stellite 6 y Colmonoy 56 alloys over structural steel 42CrMoS4 by LMD **without preheating** the base material.

- Material Deposition Rates **higher than 0.5 kg/h** and coating layer height **higher than 0.5 mm** have been obtained with all analyzed coating alloys.

- In the coatings, the obtained hardness values are higher than those established by the powder manufactures and than the hardness of the base material:
  - 62HRC en el Eutroloy 16606
  - 54HRC en el Stellite 6
  - 56 HRC en el Colmonoy 56.

- In general, the obtained powder efficiency is lower than 60%.

- It is recommended to use powder flow rates lower than the correspondent to the 50% of the maximum rotation speed of the powder feeder.
Conclusions

▪ With the Colmonoy 56 alloy porosity has been observed and with the Stellite 6 alloy powder fluidity problemss have been observed.

▪ Thus, it is recommended to use **EuTroLoy 16606** alloy:
  - Layer Height, H: 0.76mm
  - Powder efficiency, ε=43%
  - Material Deposition Rate, MDR: 0.57 kg/h
  - Productivity, Pr= 1581 mm²/min

▪ **Powder Exposition Values acceptable** and below the limits established by Michelin

▪ The machine is a **CLASS 1** Laser System
Future work

- Validation of the coatings in **real working conditions** by manufacturing real extrusion screws.
- Testing with **continuous coaxial nozzle**, with the aim of achieving **powder efficiencies** up to 90%.
- To analyze the **effect of the gravity** for using the **continuous coaxial nozzle** when working with the **inclined head**.
- To test the **filtration, aspiration and automatic cleaning** systems.
- To install the **LMD equipment** at Michelin facilities.
Future work

- To analyse **other applications** for extrusion screws:
  - Manufacturing of whole filets
  - Coating of the side of the filets
  - Manufacturing of new features
Acknowledgements

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www.photonics21.org
www.effra.eu
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