Artigo

NEW PROCESS BASED ON ROTATE SYSTEM AND EHLA LASER CLADDING PARAMETERS FOR NICKEL AUTOMOTIVE BRAKES

NOVA SISTEMÁTICA BASEADA EM SISTEMA ROTACIONAL E PARÂMETROS DE LASER CLADDING POR ALAV PARA RECOBRIMENTO DE FREIO AUTOMOTIVO COM NÍQUEL

NUEVO SISTEMA BASADO EN ROTACIÓN Y PARÁMETROS DE LASER CLADDING POR ALAV PARA RECUBRIMIENTO DE FRENOS DEL AUTOMÓVILES POR NÍQUEL

DOI: 10.56083/RCV4N6-051
Receipt of originals: 05/03/2024
Acceptance for publication: 05/24/2024

Paulo Paiva Oliveira Leite Dyer
Doctor of Science
Institution: Instituto Tecnológico de Aeronáutica
Address: São José dos Campos, São Paulo, Brasil
E-mail: paulo_dyer@yahoo.com

Ana Cláudia Costa de Oliveira
PhD in Space Engineering and Technology
Institution: Instituto Nacional de Pesquisas Espaciais
Address: São José dos Campos, São Paulo, Brasil
E-mail: aclaudiacosta21@gmail.com

Carolina Hahn da Silveira
Doctor of Engineering in Inorganic Chemistry
Institution: Universidade Federal de Santa Maria
Address: Santa Maria, Rio Grande do Sul, Brasil
E-mail: cahdsilveira@gmail.com

Naiara Vieira Le Sénéchal
Master in Materials Science
Institution: Instituto Militar de Engenharia
Address: Rio de Janeiro, Rio de Janeiro, Brasil
E-mail: naiara@ime.eb.br
**Flavio Morilla Camargo**  
Bachelor of Business Administration  
Institution: Centro Universitário de Jaguariúna  
Address: Jaguariúna, São Paulo, Brasil  
E-mail: flavio.morilla@optbrasil.com.br

**Silvelene Alessandra Silva**  
Post-Doctorate in Laser Cladding  
Institution: Instituto de Estudos Avançados  
Address: São José dos Campos, São Paulo, Brasil  
E-mail: lenisoni@uol.com.br

**Maria Margareth da Silva**  
Postdoctoral Degree in Materials and Metallurgy  
Institution: Université De Poitiers  
Address: Poitiers, França  
E-mail: meg@ita.br

**Getúlio de Vasconcelos**  
Doctor of Science  
Institution: Instituto de Pesquisas Energéticas e Nucleares  
Address: São Paulo, São Paulo, Brasil  
E-mail: getuliovas@gmail.com

**ABSTRACT:** The whole world depends on land vehicles such as trucks, cars and motorcycles to meet essential demands. As a result, PM2.5’s emissions become to centre attention; being that, 20% comes from brake-disc and pad friction. In view of this problem, this paper presents a new method for brake-discs laser cladding; using nickel (coating) and rotation system. To this end, was used the high-speed laser application system (EHLA); consisting of: an ytterbium laser, robotic arm, rotating shaft with stepper motor and coat powder aspersion system. The results shown a viability of this technique. With the following parameters: tangential velocity of scanning “v_s” 9-11mm/s, power efficiency “E” of 70-75% and deposition rate “µ” of 4g/min. Producing homogeneous, well-anchored coatings. With high densification.

**KEYWORDS:** brake discs, EHLA, laser coating, nickel.

**RESUMO:** O mundo depende dos veículos terrestres como caminhões, carros de passeio e motocicletas para atender demandas essenciais. Com isso, as emissões de MP2,5 despertam atenção; sendo que 20% decorrem do atrito entre pastilha e discos de freio. Em vista deste problema, este artigo apresenta um novo método para revestir discos de freio à laser; utilizando níquel (revestimento) e sistema de rotação. Foi utilizado um sistema de aplicação de laser de alta velocidade (ALAV); composto por: laser de yttérbio, braço robótico, eixo rotativo com motor de passo e sistema de aspersão de pó de revestimento. Os resultados mostraram a viabilidade da técnica. Determinando os seguintes parâmetros: velocidade tangencial de
deposição “\(v_s\)” 9-11mm/s, eficiência da potência “\(E\)” 70-75% e taxa de deposição “\(\mu\)” de 4g/min. Produzindo revestimentos homogêneos e bem ancorados, com elevada densificação.

**PALAVRAS-CHAVE:** discos de freio, ALAV, revestimento à laser, níquel.

**RESUMEN:** El mundo entero depende de vehículos terrestres como carretas, coches y motocicletas para satisfacer las demandas esenciales. Como resultado, las emisiones de PM2,5 se han convertido en el centro de atención; siendo que el 20% proviene de la fricción de los discos y pastillas de freno. En vista de este problema, este artículo presenta un nuevo método para el revestimiento láser de discos de freno, utilizando níquel (revestimiento) y un sistema de rotación. Para ello, se utilizó el sistema de aplicación láser de alta velocidad (ALAV); compuesto por: un láser de iterbio, brazo robótico, eje giratorio con motor paso a paso y sistema de aspersión de polvo de recubrimiento. Los resultados mostraron la viabilidad de esta técnica. Con los siguientes parámetros: velocidad tangencial de barrido “\(v_s\)” 9-11mm/s, eficiencia energética “\(E\)” del 70-75% y tasa de deposición “\(\mu\)” de 4g/min. Produciendo recubrimientos homogéneos y bien anclados. Con alta densificación.

**PALABRAS CLAVE:** discos de freno, ALAV, revestimiento láser, níquel.

1. **Introduction**

The latest census; by international road agencies; point out that road transport accounts for almost 93% of all locomotion means (UNECE, 2021; FHWA, 2021). With this, for last three decades until today, there has been growing the concern about health problems and deaths. In face of air pollution generated by motorcars (Granados, 1998; Ali et al., 2008). In fact, according World Health Organization's (2022) databank, the largest gases issue (greenhouse gases, perchlorate, sulphates and so on.) and persistent particulate matter (PM2.5) comes from mopeds.
However, a significant PM2.5’s portion come from other land vehicles repercussions; mainly by the pad/disc-brake friction effect (Wei et al., 2022; Ajayi et al., 2024; Hagino, 2024). This is an unnoticed consequence; generating air-pathogens that remains in suspension for long periods. Imputing under worldwide population various health problems and arising deaths (WHO 2022; Yin et al., 2021; Southerland et al., 2022; Tiseo, 2023).

Recent researches shown viable brake discs processing by EHLA laser cladding; in terms of final quality (Arias-González et al., 2016). Nevertheless, persist a great research opportunity on this approaching. Concomitantly, this paper presents a new proposal for laser coating motorcars brake discs. Considering the EHLA technique with a rotation system. using a Yb fibre laser, 6mm diameter beam diameter \( b_d \) and 1500 W of power \( P \). Using a rehabilitated grey iron disk, as a substrate and a nickel powder, as a coating. Next, a macro analysis of cladding surface and cross section was performed by optical microscopy (OM); evaluating the clad quality as function of tangential speed; or beam velocity of scanning; \( v_s \), power efficiency \( E \) and powder deposition rate \( \mu \) parameters. The results were analysed in terms of starting parameters of morphology aspects.

2. Contextualization

The world moves by road, according to the latest census by the European Economic Commission (UNECE, 2021) and the US Federal Highway Administration (FHWA, 2021). Where, more than 93% of worldwide is transportation carried out by land vehicles; to the detriment of other means of transport, such as sea, river, air and rail. With this, there is a growth in the traffic of vehicles, according to Placek (2024). With this database showing a sharper increase in last 4 years, as Figure 1[A] graph shown.

As a result, the air quality impair is increasingly, especially in large cities, affirm Fussel et al. (2022). In face of alarming vehicular contribution
to air pollution (WHO, 2022; Tiseo, 2023). According last World Health Organization report (2022), these air effluents are mostly composed (76%) of greenhouse gases, such as CO₂, NOₓ, CH₄ and vapours. In Addition, highly persistent particulate matter PM2.5 (24%), which remains suspended for long periods. As Ali et al. (2008) explain, it’s occurred due to particle smaller size (<2.5µm); than other particulates matter. Being produced into engines (during the fossil fuels combustion) and other motorcars repercussions (brake systems, and others). With this, Selley et al. (2020) also emphasize that these pathogens are transported for kilometres, spreading carcinogenic propensities. And so, accumulating in lungs and fatty tissues; causing more than 4 million direct deaths a year, worldwide.

However, in a biased air pollutant scenario, the causative “agents” end up being poorly detailed, explains Selley et al. (2020). Thus, for Fussel et al. (2022) it is common to mopeds labelling as a greater responsible. Although; even though they really are; other 20% of total PM2.5 emissions come from the automobiles braking system. Thus releasing, about millions of metric tons of PM2.5 (per year), due to disc/pad friction. Consequently, causing almost 1 million deaths per year worldwide, as shown in the graph in Figure 1[B].
Figure 1. Worldwide vehicle traffic grows with emissions and attributed deaths.

Source: Adapted from: Selley et al. (2020); Southerland et al. (2022); WHO (2022); Tiseo (2023) and Placek (2024).

In this context, Selley et al. (2020) call automotive braking systems a “little-known socio-environmental problem”, which is as terribly damaging as moped emissions. Where, the grey-iron (GI), its base material (pad/disc) is effective; and shouldn't be altered; considering its operability within the standards (Tonolini et al., 2021). According to Djafri et al. (2014), GI presents good shear and wear resistance, with an easy-workability at foundry. In addition, its microstructure presents porous; assuring a good factory’s useful life. However, promoting the PM2.5 dispersion during its use.

In the field of possibles “wear-improvements”; applied in metal processing chains; Vilar (1999) highlights the role of EHLA (Extreme High-speed Laser Application) laser cladding treatments. Where, a focused OEM beam reaches temperatures higher than metals fusion; possibility the anchor under a surface of more resistant alloys. This makes it possible through metallurgical bonds under the coating/substrate of interest. Where, the coating material is asperged in “powder” form into the focal laser-beam region. As a result, the powder and substrate fuse at the same time, as shown in Figure 2[A]. Thus, the system transfers sufficient energy to provide
a satisfactory metallurgical bonding (Svetlizky et al., 2022).

In this way, Olofsson et al. (2020) points out that in the case of brake discs, the EHLA laser cladding process could minimize the emission of PM2.5; improving its wear. To this end, the EHLA laser cladding parameters must be adjusted; as function of CI’s porosity. As well, the coating uniformity; considering the disk geometry (Arias-González et al., 2016). Noting that each single line coating (or “track”) must be overlap "Ov" its neighbourhood at 50% rate. Where, this Ov is applied to each track width “W”; as illustrated by Figure 2[B] (Shi et al., 2021). With this, studies shown the advantages of rotating systems use; as Figure 2[C] shown (Olofsson et al., 2020).

Figure 2. Schemes of laser cladding, track layout and EHLA with a rotation system.

Source: Adapted from: Arias-González et al. (2016); Santos (2017) and Li et al. (2019).
Shi et al. (2021) completes that for coat-material, the use of nickel-based alloys provides good anchorage in grey iron. Likewise, Nickel-based alloy provide a significantly 1.5 times wear resistance greater than GI. In addition, with a satisfactory cost/benefit ratio compatible to disk's production cost; at a viable industrial chain.

From this perspective, were observed a standardization lack for brake disc laser cladding. Thus, in this paper a new process based on rotate system and EHLA were proposed for brake-discs coating. With this, a conventional rehabilitated automobile brake-disc was used as substrate. In addition, a Nickel powder was used as a coating. For experimental step, was used an Ytterbium fibre laser, with 6mm of beam diameter \( b_d \) and 1500 W of maximum power \( P \). With the set EHLA carried and operated by a robotic arm; using program routines. Next, a macro analysis of cladding surface and cross section was performed by optical microscopy (OM); evaluating the clad quality as function of tangential speed; or beam velocity of scanning; \( v_s \), \( P \), trajectory type, focal length \( d_f \) and powder fed rate \( \mu \) parameters.

3. Methodology

The methodology adopted includes materials and procedures. As materials, were used a P/M Ni XF Master-Melt PLUS nickel powder as a coating; with properties as granulometry (obtained by sieving), morphology (images obtained by a Tecsan Vega Scanning electron microscope - SEM) and elemental composition (obtained by an Energy dispersive spectroscopy - EDS - sensor coupled to SEM Tecsan Vega) showed in Figure 3.

As a substrate were used two "Bd2064" reconditioned brake disk (D01 and D02); with composition according to Figure 4. Where, the D01 and 02 surfaces were subdivided into three regions: Internal Superior Region (ISR), External Superior Region (ESR) and Inferior Region (IR); for different coating parameters performing, as Figure 3[B] also shown.
Figure 3. Coating properties.

Particle size distribution

SEM 100X increase

EDS elem. comp.

N 99.98 %Weight
C 0.0049 %Weight
Si 0.2 %Weight
Fe 0.0012 %Weight
C 0.003 %Weight
Si 0.0003 %Weight
Ph 0.0003 %Weight

Source: Authors (2024).

Figure 4. Disks substrates properties.

Dimensions of D01 and 02 with the delimitation of regions

EDS elem. comp.

Fe: 76.3 %Weight
O: 14.0 %Weight
Cl: 13.3 %Weight
Si: 1.70 %Weight
Mn: 0.40 %Weight
S: 0.20 %Weight
P: 0.10 %Weight

Reference: Authors (2024).

For the experiment, were built two set-ups; as Figure 5 shown; they are: robotic arm moving by a command in "pendant" control and programming – for D01 and 02 (Figure 5[A]); and fixed robotic arm, with movement executed by a coordinated table (CNC-T) below the rotate system – for only D02 (Figure 5[B]). Where, the irradiation being fed by a powder feeder, with argon gas providing the powder loading for EHLA and sample
shielding (with flow of "s/f" and "l/f", respectively). For rotation system, in other hand, were used a gear box coupled to 15 and 48mm diameter pulleys (motor and reducer, respectively), with the assembly being rotated by an "AT5618L0308 3V/3" stepping motor. For rotating programming were employed G-code "F" commands for angular velocity (RPM); implemented in the Universal G-code Sender platform software, as a routine or isolated commands. For arm moving, however, was used robot’s manual controller (control pendant) and RoboDk software to implement programming routines for a "spiral" coating tray.

For pendant and CNC-T, were made moves in orthogonal direction to "v_s"; being that only CNC-T difference was its greater precision. The "spiral track", in other hand, was composed of two-line segments with \( v_s = 0.1 \) mm/s and angular speed "w_s" varying. Initially, under D01-ISR, concentric circular tracks were deposited; varying \( R_c \) circumference radius by 3 mm. Next, on D01-ESR was deposited the spiral track, with F varying per rotation and arm moving under a defined programming path. For both D01-ISR and ESR tracks were defined a \( \mu = 4 \) g/min and \( s_f = l_f = 15 \) l/min; imbued with an initial irradiation "E_i" of 40% passage and deposition "E_\mu" of 70-80%,
passing from 1 to 2 times \( E_{\mu(1 \ or \ 2)} \). Sequentially, under IR-D01 were deposited arc-tracks. With a new F-command routine, \( s_r = l_r = 15 \ \text{l/min} \), \( E_{\mu} = 75\% \), \( \mu = 4 \ \text{g/min} \) and no prior irradiation; according to Table 1.

The tracks were timed, obtaining gyration time \( t_g \) for each track. Then, D01 surface macro photography was rasterized using AutoCad 2020. Obtaining \( A_l \) arc/circumference lengths, \( R_c \), \( \alpha_l \) length angles, \( w_s \) and \( v_s \), both calculated through classic angular speed equation. Likewise, were obtained 10 and 25X increase OM micrographs, using a stereoscope and microscope (both Zeiss).

<table>
<thead>
<tr>
<th>Tracks</th>
<th>( F )</th>
<th>( E_{\mu(1)} )</th>
<th>Type</th>
<th>Tracks</th>
<th>( F )</th>
<th>( E_{\mu(1)} )</th>
<th>( E_{\mu(2)} )</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>D01-ISR-T1</td>
<td>264</td>
<td>70</td>
<td>Circle</td>
<td>D01-ISR-T3</td>
<td>225</td>
<td>75</td>
<td>75</td>
<td>Circle</td>
</tr>
<tr>
<td>D01-ISR-T2</td>
<td>251</td>
<td>70</td>
<td>Circle</td>
<td>D01-ISR-T4</td>
<td>210</td>
<td>75</td>
<td>80</td>
<td>Spiral</td>
</tr>
<tr>
<td>D01-ISR-T1</td>
<td>238</td>
<td>75</td>
<td>Arc</td>
<td>D01-ISR-T6</td>
<td>180</td>
<td></td>
<td></td>
<td>Arc</td>
</tr>
<tr>
<td>D01-ISR-T2</td>
<td>200</td>
<td></td>
<td></td>
<td>D01-ISR-T7</td>
<td>120</td>
<td>75</td>
<td>75</td>
<td>Arc</td>
</tr>
<tr>
<td>D01-ISR-T3</td>
<td>120</td>
<td></td>
<td></td>
<td>D01-ISR-T8</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D01-ISR-T4</td>
<td>220</td>
<td></td>
<td></td>
<td>D01-ISR-T9</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D01-ISR-T5</td>
<td>200</td>
<td></td>
<td></td>
<td>D01-ISR-T10</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D01-ISR-T6</td>
<td>160</td>
<td></td>
<td></td>
<td>D01-ISR-T11</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D01-ISR-T7</td>
<td>180</td>
<td></td>
<td></td>
<td>D01-ISR-T12</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D01-ISR-T8</td>
<td>120</td>
<td></td>
<td></td>
<td>D01-ISR-T13</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Authors (2024).

The D02 experiments began with initial linear and off-set trajectories under ESR stopped disk. These experimental tracks “D02-E-T” presented ablative and cavities effects; due to GI’s heat-cumulative effect. Thus, \( d_r \) was changed 4 mm above original (12.6 mm). Next, experiments continued with new \( d_r \); performing arc-tracks under IR with low F (\( v_s = 2-6 \ \text{mm/s} \)) varying \( E_{\mu} \) and \( \mu \) by arc path; as Table 2 shown. Sequentially, were evaluated the D02-IR thickness variation effect; due to disk’s “venting grooves”. With this,
were obtained a correlation between micrographs of tracks surfaces and cross-sections; and fusion macro photos; obtained by STC-HD203DV cam.

Table 2. Next parameters with new $d_f$ and venting grooves evaluating under D02.

<table>
<thead>
<tr>
<th>Tracks</th>
<th>Path</th>
<th>$E_{\mu(1)}$</th>
<th>$F$</th>
<th>$\nu_s$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR-T1</td>
<td>a</td>
<td>60</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>70</td>
<td>140</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>75</td>
<td>6</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>IR-T2</td>
<td>a</td>
<td>70</td>
<td>70</td>
<td>2</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>75</td>
<td>70</td>
<td>2</td>
<td>5.7</td>
</tr>
<tr>
<td>IR-T3</td>
<td>a</td>
<td>75</td>
<td>67</td>
<td>3</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>67</td>
<td>70</td>
<td>3</td>
<td>5.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tracks</th>
<th>Path</th>
<th>$E_{\mu(1)}$</th>
<th>$F$</th>
<th>$\nu_s$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR-T4</td>
<td></td>
<td>60</td>
<td>70</td>
<td>3</td>
<td>5.7</td>
</tr>
<tr>
<td>IR-T5</td>
<td>a</td>
<td>60</td>
<td>70</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>53</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>IR-T6</td>
<td></td>
<td>60</td>
<td>70</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>IR-T7</td>
<td></td>
<td>60</td>
<td>70</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>IR-T8</td>
<td></td>
<td>60</td>
<td>70</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>IR-T9</td>
<td></td>
<td>60</td>
<td>70</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Source: Authors (2024).

The last tracks analysis resulted in the choice of ESR (without venting grooves) and the original $d_f$ return; for the latest coating. With this modifications, "D02-ESR-T" was segmented into several concentric circles; or lanes; with different Rc on ESR-D02 region. For this purpose, were fixed an $E_{\mu} = 70\%$, $\mu = 4$ g/min and $F = 850$RPM ($\nu_s = 11$ mm/s) with same $t_g = 20s$ (by lane), from inside to outside. Where, the laser beam was maintained fixed. With this, $R_c$ off-set (from 300µm) was made by MR-25 orthogonal movement; according to set-up 2. D02-ESR-T was analysed throughout other process-chart; containing $t_g$ and $A_l$ data as a function of lane-tracks OM cross sections micrographs. Pointing that for all sectional micrographs, the samples were sectional sliced, Bakelite embedded and metallographically prepared with sandpapers grits of: 80, 120, 220, 320, 400, 600, 800, 1200; 0.5µm alumina polishing and treated with 4% Nital reagent.

4. Results and Discussions

The initial evaluation showed that the most part of $\nu_s$; under D01; obtained from Figure 6 raster-photo; were considered high (12-27 mm/s) for EHLA laser cladding; as Table 3 shown. According to Pellizzari et al. (2022),
high vs produces unsatisfactory dilution "D" and clad angles "a". In addition, don't producing metallurgical bonding and allowing the "Balling1" formation.

Furthermore, Figure 7 process-chart shown a 9-11 boundary of vs for well coating. In this range; with a single EHLA deposition or $E_{\mu(t)}$; the arc-claddings shown uniformity and absence of ablation and Balling formation. While, for vs > 11 were observed many balling or no-cladding occurrence. In contrast, for vs < 9 were observed promising results. Consequently, the D02 experimentations were plausible; with low vs and variations of $\mu$ and $E_{\mu}$.

Figure 6. D01 tracks raster-photos with dimensions.

1 The balling effect is a problem that often frequently occurs in the selective laser melting forming process and seriously affects the surface precision (Ramakrishna & Sundararajan, 2019).
Table 3. Results of tracks rasterization from initial parameters under D01.

<table>
<thead>
<tr>
<th>Tracks</th>
<th>$v_s$ mm/s</th>
<th>$w_s$ RPM</th>
<th>$R_c$ mm</th>
<th>$A_l$ mm</th>
<th>Tracks</th>
<th>$v_s$ mm/s</th>
<th>$w_s$ RPM</th>
<th>$R_c$ mm</th>
<th>$A_l$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>D01-ISR-T1</td>
<td>12</td>
<td>20</td>
<td>35</td>
<td>218</td>
<td>D01-ISR-T3</td>
<td>11</td>
<td>16</td>
<td>41</td>
<td>255</td>
</tr>
<tr>
<td>D01-ISR-T2</td>
<td>11</td>
<td>18</td>
<td>38</td>
<td>237</td>
<td>D01-ISR-T4</td>
<td>10</td>
<td>14</td>
<td>44</td>
<td>274</td>
</tr>
<tr>
<td>D01-ISR-T3</td>
<td>11</td>
<td>18</td>
<td>38</td>
<td>237</td>
<td>D01-ESR-T</td>
<td>15</td>
<td>14</td>
<td>44</td>
<td>203</td>
</tr>
</tbody>
</table>

Source: Authors (2024).

Figure 7. D01 tracks process-chart.

Source: Authors (2024).
Sequentially, some discussions about other parameters were brought into light. From Figure 8; of D02 raster-photo; were obtained $A_i$, $a_i$ and $R_c$; being correlated with $E_{\mu}$ and $\mu$ variation. However, $\mu$ and $E$ variation presented a minor influence at low $v_s$. Where, for $\mu = 5.7$ g/min was observed Balling formation thorough the track. The $\mu = 4$ g/min, on the other hand, imbued the best cladding quality; with $E_{\mu} = 60$ to $\sim 70\%$; as Figure 9 process-chart shown. Although, low $v_s$ produced cladding quality variation as function of IR thicknesses difference of venting grooves. In addition, was observed GI’s ablation under lower thicknesses; consequently, don’t allowing the coating, as Figure’s 10 process-chart shown. Where, the fusion pics shown a material spreading; every 2 seconds (central $t_g$); producing a clad absence, also observed in surface micrographs. Likewise, the MO cross sections; as Figure 11 shown; corroborate this effect, showing a heat cavitation occurrence.

Figure 8. D02 tracks raster-photos with dimensions.
Figure 9. Process-chart of D02-IR-T1 to T3 tracks.

Source: Authors (2024).

Figure 10. Process-chart of D02-IR-T4 tracks.

Source: Authors (2024).

Figure 11. Cross-section and surface of D02-IR-T7 OM micrographs.

Source: Authors (2024).
The process-chart of Figure 11 shown, in section [A], a considerate substrate displacement. With a large heat cavity formation under the thinnest IR thickness. While in section [B], a smaller cavity is observed, but with similar effect. In addition, both sections don’t present a cladding region. From these results, the parameters of the last experiment were plausible; producing best results. Where, the lanes cross sections shown uniformity and anchoring points, as Figure 12 shown. Where, lanes cross sections in 4 $t_g$: start/end, near start, middle and near end. Where, start/end or $t_g = 0/21s$ is the same start and end lanes point, due to circular characteristic; allowing a layer accumulation. The other sections: $t_g = 5s$ (near the beginning), 10s (middle) and 15s (almost at the end), on the other hand, shown similarity between them. In this latter ($t_g = 15s$), individual lane melt pictures were also correlated. Whit $v_s$ (Figure 14) variation minor affecting the EHLA deposition, being compensated by temperature increase.

Furthermore, a high occurrence of flaws and macropores, dense clad regions were observed; as well as the lanes densification, as Figure 15[A] micrographs shown. Where, the lanes merging allowed the coat machining. Likewise, in [B] detailed MO cross sections indicated the metallurgical bonding occurrence; characterized by dendritic structures visualization. In addition, a satisfactory $D = 25\%$ was obtained; according to Pellizzari et al. (2022) criteria; using Equation (1), related to Figure 16 scheme.

$$D = A_m \cdot [A_c - A_p + A_m]^{-1} \quad (1)$$

where:

- $A_c$ = coating area in mm²
- $A_p$ = macropores areas in mm²
- $A_m$ = diffusion area in mm²
Figure 12. Process-chart of D02-ISRT track lanes.

Source: Authors (2024).

Figure 13. Analysis of D02-ISRT track lanes micrographs.

Source: Authors (2024).

Figure 14. Tangential velocity variation at last experiment.

Source: Authors (2024).
5. Conclusion

The research's results initially provided information about the $w_s$ controlling; as function of $v_s$. Thus, determining boundary conditions in relation to GI's porosity. To avoid adverse effects such as ablations and material spreading. Likewise, was observed the relationship between $d_r$, low $E$ and high $v_s$ in relation to Balling formation. Finally, was determined initial conditioning parameters for nickel deposition under brake discs. Concluding that the $v_s$ of laser beam is the main parameter for obtain a well cladding.

The boundary conditions defined the parameters for last experiment. In this way, were determined a $v_s = 11$ mm/s, $E_\mu = 70\%$, $\mu = 4$ g/min that produced the best results. From these new parameters, a basis for this study continuation were firmed. Thus, starting from these parameters; with proposed experimental set-up; other experimentation for future scope.
Acknowledgements

This research was funded by CNPq, under the grant: 405624/2022-0; CAPES, under the grant: 88887.285953/2018-00, and FINEP, under the grant: 25670-SUB-1.
References


LI, L.; SHEN, F.; ZHOU, Y.; TAO, W. Comparative study of stainless steel AISI 431 coatings prepared by extreme-high-speed and conventional laser


