Original Article

Investigation on metallurgical, tribological, hardness properties of spray deposited and warm rolled Al-18Pb, Al-22Pb alloys

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**A B S T R A C T**

Al-18Pb and Al-22Pb alloys were processed by a rapid solidification process known as the spray deposition technique. Gaussian or bell-shaped deposits were obtained at a pressure of 10 bar, nozzle to substrate distance of 423 mm and substrate inclination angle of 0°. Deposits obtained from both alloys were warm rolled at a recrystallization temperature of 395 °C. Microstructural analysis of deposits showed that Pb is equally distributed in the Al matrix with 60% thickness reduction. For both alloys, the decrease in thickness percentage resulted in the decrease of hardness values. Porosity was lower in spray deposits of Al-18Pb alloy than the corresponding one from Al-22Pb alloy due to the casting and rolling defects. When the Pb percentage is increased from 18 to 22 in Al-22Pb compared with Al-18Pb, the wear rate increases abnormally. The frequency of wear and coefficient of friction values of Al-22Pb alloy were also higher when compared with those of Al-18Pb alloy.

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1. **Introduction**

Aluminum (Al) alloys are extensively used in various industrial manufacturing areas such as bullet train, ships and automobiles [1], as well as in aerospace industries [2], due to their excellent properties of low weight to high strength, stiffness, good weld-ability, high corrosion resistance [3], ease of casting, and lower thermal coefficient of expansion and abrasion resistance [4]. There are various specific aluminum alloys such as Al-Si, Al-Sn, Al-Graphite, and Al-Pb that are used as bearing alloys [5]. Among these, Al-Pb alloys possess better thermal conductivity [6], corrosion resistance, frictional properties and have inexpensive and ease of production than the other alloys.

However, the processing of Al-Pb alloys is challenging due to the significant variation between specific gravity and melting point. As a result, during solidification of Al-Pb alloy, impurities settle down below the crucible. This leads to many challenges in casting by conventional manufacturing process [7]. Various processing techniques such as stir casting melt

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spinning, vortex casting, rheocasting, powder metallurgy [8], and bottom discharge and spray deposition method [9] are well known. Among these processes, spray deposition is a two-step process (i.e., melting and pouring) that facilitates chemical homogeneity due to rapid solidification [10]. Fig. 1 is a comparison between spray deposition and Metallurgy.

Ashish et al. [11] reported that the spray deposition process integrates the powder processing route in such a way that powder was not handled at any stage of the process. Mohan et al. [12] investigated the characteristics of stir cast Al-Pb alloys at fixed and variable stirring speed by varying the Pb composition. Three important findings were established. (i) Cast deposits such as Al-3.69Pb, Al-8.04Pb, Al-10.39Pb, Al-20.09Pb, Al-30.18Pb, Al-47.50Pb, and Al-55.53Pb, which were processed through friction stir casting route at a fixed agitator speed of 53 rev/s, had possession porosity values (%) of 10.07, 10.42, 10.92, 11.29, 11.68, 11.89, and 12.03, respectively. The data confirmed that at fixed stirring speeds, the porosity percentage in deposits increased when the percentage of Pb composition (by wt. %) was increased. (ii) At lower stirring speeds of 25 rev/s and 37 rev/s with fixed Pb composition of 9%, the porosity decreased by 4%. (iii) Increase in Pb content up to 20% led to a decrease in μ. Also, Pb acts as a wear protective layer due to the smearing behavior. Beyond 20% Pb in the alloy composition, μ values increased sharply due to the formation of the lead oxide layer (Pb2O3), resulting in decreased hardness. Rashmi et al. [13] investigated the microstructure and thickness uniformity of the spray deposited Al-Si-Pb alloys. Uniform thickness of spray deposit was obtained at inclination angle of 30° with the spray deposition distance of 400 mm. Microstructure analysis of these spray deposits revealed the following information: (i) Si and Pb grains were distributed along the Al grain boundary; (ii) size of Al grains were in the range of 20–30 μm; (iii) Si is about submicron to 5 μm; (iv) Pb is approximately 20 μm. Aruna et al. [14] investigated the presence of porosity in the spray deposited Al-Si-Pb alloy system and observed that the porosity was more in peripheral regions of deposit and also with more Pb content. Aruna et al. [15] also examined the mechanical behavior of the spray deposited Al-Si-Pb alloys and reported that the increase in Pb composition increased the strength and strain and decreased proof stress. The report further established that the increase in spray deposition distance from the center to peripheral regions resulted in the increase in stress as well as strain values. They also established that the increase in percentage of Si in the alloy composition led to significant improvement in tensile and proof stress. Ojha et al. [16] reported the hardness behavior of spray deposited hypoeutectic Al-Si alloys and observed that the conventionally processed Al-6.91Si and Al-10.1Si alloys possessed lower hardness than the spray deposited alloys. In the study of spray deposition distance vs. hardness behavior of the deposits, that is, Al-6.91Si and Al-10.1Si, the hardness values increased linearly with spray deposition distance up to 450 mm after which the hardness value decreased. This may be because at optimum nozzle-substrate distance (450 mm), 15–30% liquid metal obtain a good quality preform [17]. When the distance is more than that of optimum substrate distance, the amount of liquid metal reaching the substrate will be low. Therefore, it would not give a proper cohesive mass which will lead to a decrease in hardness.

Rashmi et al. [18] investigated the wear rate of spray deposited Al-Si-Pb alloys and reported that the wear rate increased with the increase in Pb content and loads. They also reported that the wear rate increased when the moving distance from center to peripheral regions is decreased. Rashmi et al. [19] investigated the sliding wear behavior of the spray deposited Al-6Si before and after cold rolling and established that the porosity was lower after cold rolling and nullified

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**Fig. 1 – Processing steps in comparison with P/M and spray forming techniques.**

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for 80% thickness reduction. For cold rolled wear samples, the wear resistance rate was improved significantly. McAlister et al. [20] established the Al-Pb equilibrium diagram. Warm rolling operation was performed, and the value of the recrystallization temperature of the Al-Pb alloy was taken from the phase diagram, that is, 0.4 Tm = 395 °C.

In spite of numerous work in this arena, investigation on metallurgical, tribology, hardness properties of spray deposited and warmed rolled Al-18Pb, Al-22Pb alloys in peripheral regions are still unexplored. In the present work, Al-18Pb and Al-22Pb deposits were obtained through spray deposited route and then warm rolled. The metallurgical, mechanical and tribological characteristics of Al-18Pb and Al-22Pb deposits were investigated for different thickness reductions.

2. Experimental

The spray deposition chamber mainly consists of (i) spray deposition unit; (ii) atomizer connected to compressor; and (iii) assembly of the atomizer, graphite crucible, induction furnace and connecting rod.

2.1. Spray deposition procedure

The spray deposition process is shown in Fig. 2. The percentages of compositions are given in Table 1, and the processing parameters are given in Table 2.

First, approximately 1 kg of Al-Pb (Source: KOVAI METAL MART, Coimbatore, Chennai, 641018. INDIA) alloy was heated in a crucible. A stopper rod blocks the flow of melts before its atomization. Argon was supplied to melt spouting through the conveyance tube. Disintegration emerged in the formation of a vast range of micro-sized globules, which were deposited over copper plate. After deposition, preform was taken out of the substrate.

The deposition was carried out for alloys Al-18Pb and Al-22Pb at a superheated melting point of 870 °C. Argon gas was released at a pressure range of 9–12 bar. The spray discharge assembly consists of a copper substrate placed over the inclined rotational system and centered to the spray hinge. The spinning movement was given to the disc driven by gears through a motor. The acceleration was given and transformed by varying the voltage, and the rotational system was rotated in horizontal direction.

2.2. Warm rolling

Al-18Pb and Al-22Pb deposits with thickness of 15 mm were obtained through the spray deposition method. Samples of size 10 mm × 10 mm were cut down from peripheral regions of the spray deposit and warmed at the at the recrystallization temperature of 395 °C. They were further rolled by using a two-high hot rolling machine for percentages of thickness reductions from 0 to 60 with a difference of 15. The rollers were operated in opposite directions, and the samples were fed from both sides.

2.3. Microstructure

Al-18Pb and Al-22Pb deposits were obtained through the spray deposited route. Samples were cut down to the size of 10 mm × 10 mm from the peripheral regions of deposits. Sharp corners were removed by a grinding machine and were processed by the traditional metallurgical polishing technique as per ASTM E3-11(2017) standard. The square shaped samples

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Fe</th>
<th>Si</th>
<th>Pb</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-18Pb</td>
<td>0.60</td>
<td>0.05</td>
<td>18</td>
<td>Bal.</td>
</tr>
<tr>
<td>Al-22Pb</td>
<td>0.51</td>
<td>0.04</td>
<td>22</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 2 – Process variables in spray forming.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt temperature</td>
<td>870 °C</td>
</tr>
<tr>
<td>Gas pressure</td>
<td>10 bar</td>
</tr>
<tr>
<td>Nozzle to substrate distance</td>
<td>38–42.3 cm</td>
</tr>
<tr>
<td>Atomizing gas</td>
<td>Argon</td>
</tr>
<tr>
<td>Melt flow rate</td>
<td>15 gm/s</td>
</tr>
<tr>
<td>Gas flow rate</td>
<td>22 gm/s</td>
</tr>
<tr>
<td>Ratio of gas to melt flow rate</td>
<td>1.25:1</td>
</tr>
</tbody>
</table>
were mounted with the binders. Mounted samples were polished with emery paper of different grit sizes <100>, <200>, <300>, <400> in perpendicular direction and were cleaned with kerosene. Subsequently, wheel cloth polishing using an emulsion of Al₂O₃ was done at low rpm values, and the samples were dried with an air dryer. Then the samples were etched with Keller’s reagent (1% HF, 1.5% HCl, 2.5% HNO₃ by volume and remaining water) to obtain clear grain boundaries and were examined under Leitz optical microscope of JEOL JXA890A. It is necessary to determine the apparent and true porosity of warm rolled sample surface for various thickness reductions in peripheral regions, and their average values were considered. Apparent densities were calculated by Archimedes principle, following the ASTM B328-96 practice.

\[
\text{Apparent Porosity} = \frac{(\text{Soakedwt} - \text{Drywt})}{(\text{Soakedwt} - \text{Suspendedwt})} \times 100 \ldots (1)
\]

\[
\text{True Porosity} = \frac{1}{1 - \left(\frac{\text{Apparent Sp. Gr.}}{\text{True Sp. Gr.}}\right)} \times 100 \ldots (2)
\]

2.4. Hardness

Vickers Hardness Number (VHN) for all unrolled and warm rolled samples was measured by Vickers test mode HPO 250 at 16 kg load as per ASTM E92-17, by moving the indenter to multiple locations of the sample. The average hardness value was then calculated from samples of different percentage thickness reductions.

\[
\text{VHN} = \frac{1.8544 F}{d^2} \ldots \ldots \ldots \ldots \ldots (3)
\]

where F is in kgf and d is in mm.

\[F = \text{Force}, \quad d = \text{Arithmetic mean of the diagonals.}\]

2.5. Wear testing

Table 3 represents the processing parameters in pin on disc type wear testing machine for determination of wear rate in spray deposits of Al-18Pb and Al-22Pb alloys.

Wear testing machine consisted of heat evaluated and carbon chromium steel disc (having high hardnass 60 HRC and surface roughness about 0.4 μm) and a varying speed DC motor with a maximum rotational speed of 1450 rpm, connected via belt and pulley system. The set-up was such that a sample governor presses the test model with its flat end, sliding against the rotating disc surface and can be moved forward and backward directions. All the operations were executed with dry sliding circumstances at standard operating conditions of 25 °C and 62% room humidity. For wear test, samples were machined and polished. The steel sphere was also grounded to the smooth finish. Brasso and acetone were used to degrease the pair of test samples and steel disc. The samples were kept in contact with the chosen track by fixing it in a holder. After each run, the test samples were wiped with acetone and were washed with water. Weight of each sample was recorded at start and end points of run, and the wear rate was calculated from the weight loss. Graphs were plotted between the weight loss and sliding distance, sliding velocity and coefficient of friction, sliding speed and load to Al-18Pb, Al-22Pb deposits at a constant sliding distance of 0.75 m/s at about 30 min. In the second set of experiments, the load was varied in the range of 1 to 5 kg with the sliding time of about 30 min.

3. Results and discussions

3.1. Shape

Spray deposition distance is the distance between tip of nozzle and the rotor. Table 2 represents the processing parameters used for trials with increasing spray deposition distances of 38 cm (Fig. 3a), 40 cm (Fig. 3b), and 42.3 cm (Fig. 3c). For 38 cm and 40 cm distances, uniform thickness was not attained due to the solidification of molten metal in the central region. In addition, pressure and pouring time could not be controlled. When the spray deposition distance was increased to 42.3 cm, semi-solid droplets fell rapidly over the surface of the copper substrate. As a result, an increase in the deposit thickness was observed at the center of substrate. The remaining molten metal was solidified above the center giving a proper shape for the deposit. The rate of mass flux can change the shape of deposits. A considerable number of micro-sized droplets were produced when Argon gas hit the molten metal steam. While lighter droplets were scattered over the surface of spray cone, the heavier ones were confined to the center of the cone. As a result, mass distribution showed normal distribution along the cross-section of spray cone. As the peripheral surface area of spray cone was larger than its center, spray deposits gained a shape whose height was more at center than the peripheral portion. At 33 cm and 40 cm deposition distances, the major portion of molten metal was deposited on the center of cone axis, leading to gas porosity in the deposits. However, when the deposition distance was at 42.3 cm, the molten metal was converted into semi-solid particles and stuck uniformly over the substrate.

Then samples of size 10 mm × 10 mm × 3 mm were prepared from the central portion of the spray deposit of Al-18Pb and Al-22Pb alloys and rolled for four passes. The parameters

<table>
<thead>
<tr>
<th>Sliding distance (m)</th>
<th>Applied load (kg)</th>
<th>Sliding time (min)</th>
<th>Sliding speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>1-5</td>
<td>30</td>
<td>0.70</td>
</tr>
<tr>
<td>1300</td>
<td>4</td>
<td>20-90</td>
<td>0.20-1.20</td>
</tr>
</tbody>
</table>
used for the warm rolling process are given in Table 4. After each rolling process, the samples were cooled to ambient temperature using water. The cracks observed at 60% thickness reduction are depicted in Fig. 4.

3.2. Microstructural and porosity features

Optical microstructures of the spray deposited Al-18Pb and Al-22Pb alloys before rolling are represented in Fig. 5. In both alloys (Al-18Pb Fig. 5a and Al-22Pb Fig. 5b), Pb was homogeneously distributed in the Al matrix and had equiaxed morphology. Pb was present along and within the grain boundaries. The phases were identified with the help of Energy Dispersive Spectroscopy (EDS) technology. Bright region depicting Al phase and dull/black region depicting Pb were represented in Figs. 5c and 5d, and their color dot mappings were represented in Figs. 5e and 5f. The average grain sizes of Al and Pb in both deposits were in the range of the 42–48 μm and one submicron to 5 μm, respectively. It is notable that an increase in Pb percentage affected the average grain size of the deposits. Few pores with the size of 18–22 μm were observed in both deposits of Al-18Pb and Al-22Pb alloys before rolling. Pores were obtained due to casting which was also called cast porosity.

Microstructural analyses of peripheral regions were done for both spray deposited alloys. The majority of grains
Fig. 5 – Optical microstructures of spray deposited Al-alloy contains (a) 18Pb, (b) 22Pb, (c) Al-rich EDS mapping, (d) Pb-rich EDS mapping, (e) Al-color dot mapping, (f) Pb-color dot mapping.
obtained in both Al-18Pb and Al-22Pb deposits were finer than the analogs obtained ingot deposit, and the mechanism for the difference in nature is explained as follows. The grain size depends upon the heat flow condition. When the spray hits the deposition substrate, rapid heat transfer takes place due to conduction through the substrate. Consequently, fine equiaxed grain structure evolves from the bottom of substrate. The increase in deposition thickness decreased the rate of heat transfer. At a particular thickness, heat flux reaching the surface is balanced by the heat flow rate from the preform, establishing a steady heat flow condition. Therefore, the grain size becomes uniform and continues growing until the steady state deposition stage cease to exist. This heat flow condition during deposition results in no variation to the microstructure of the entire deposit. In addition, other factors contributing to formation of equiaxed grain size are (1) dendrite arm fragmentation, and (2) growth and amalgamation of dendrite fragments during solid state cooling. In dendrite arm fragmentation mechanism, the dendrite arms are the major cause for equiaxed grain formation. This happens because of development of semi-liquid and semi-solid layer on surface upon concurrent arrivals of liquid, solid and semi-liquid droplets. When solid and semi-solid droplets mix with the deposit surface, dendrite arm fragments are produced. These fragments act as nucleation spots for equiaxed grain development.

Optical micrographs of spray deposited and warm rolled specimens for percentage thickness reductions or passes (i) 15%, (ii) 30%, (iii) 45%, and (iv) 60% in peripheral regions are represented in Figs. 6a–6d (Al-18Pb) and 7a–7d (Al-22Pb). As the percentage thickness was increased from 15 to 60%, the grain length of Al-18Pb and Al-22Pb alloys increased along the rolling direction. Other observations are as follows: (i) Pb was distributed uniformly along the grain boundaries, (ii) For thickness reductions of 15%, 30%, 45% and 60%, average grain size of Al was 42, 38, 32 and 28 μm, respectively, whereas Pb was from one micron to 10 μm.

As shown in Figs. 6a–6d, grains were elongated along the rolling direction and the width of grain boundary increases with thickness reduction. So, as a result, the average length of Al-grains also increased. In Figs. 6(a) and 6(b), the average lengths of Al-grains are 25–35 μm. In Figs. 6(c) and 6(d), the average length of Al-grains is 35–45 μm. Few cracks called as crack porosity were also visible after rolling. Casting porosity (Fig. 8(c)) and crack porosity (Fig. 8(b)) were also observed in Al-18Pb deposits for all the thick reductions. Porosity decreased as the thickness reduction increased from 15% to 60% (Figs. 6(d) and 7(d)) and almost eliminated at maximum thickness reduction of 60%. Decrease in porosity is due to restacking and rearrangement of spray deposited particles. Beyond this, plastic deformation becomes the principle mechanism of densification during rolling, where pore elongation along the direction of rolling concurrent with fragmentation results in small pores. This process of elongation and fragmentation of pores continues while rolling. Upon rolling, the width of the pores becomes smaller and the opposite faces of the pores crumble due to which casting porosity is eliminated. The presence of any oxide layer within the pores ruptured the pores due to deviatoric stresses. After second pass warm hot rolling, the preform tends to be uniform and variation of coarser and finer grains decreases. Significant amount of recrystallized grains were observed near the grain boundaries (Figs 6b and 7b). The size of dynamic recrystallized grains notably increased after first pass rolling processes. The shape was extended along the rolling direction. It may be due to dynamic grain growth, which was important at higher temperature (673 K). After third pass warm rolling, the dynamic recrystallized grains continuously grow towards fibrous shape (Fig. 6c and 7c). The grains having higher length to width ratio broke during this process. This microstructure was remarkably refined and possessed lamellar boundary structure. Large sub-micron size ultrafine grains were also detected. Figs. 6(d) and 7(d) show grain inclination dispensation diagram of the

![Fig. 6 – The micrographs of sprayed and warm rolled Al-18Pb alloy for various percentage thickness reductions: (a) 15%, (b) 30%, (c) 45%, and (d) 60%.](image-url)
Fig. 7 – The micrographs of sprayed and warm rolled Al-22Pb alloy for various percentage thickness reductions (a) 15% (b) 30% (c) 45% and (d) 60%.

Fig. 8 – SEM graphs of (a) spray cast Al-18%Pb before rolling (b) 60% rolled Al-18%Pb (c) 60% rolled Al-22%Pb alloy.
spray-formed from Al-18Pb and Al-22Pb alloys after third pass warm rolling.

In SEM graphs represented in Figs. 8(a)-8(c), the white region belongs to Al and dark region represents Pb. With the increased thickness percentage of samples, the grain size of Al decreased, whereas Pb grain size remained constant. In this case, the grains were refined to very fine sizes due to expansion and compression temperatures. The grain refinement is better in Al-22Pb alloys when compared with Al-18Pb as the entire surface in Al-22Pb was covered by the lubricating thin film. Tomar et al. found that Al-Si-Pb alloys (with varying Pb composition 0%, 10% 20% and 30%) when processed through spray deposition (samples not undergone any cold rolling, warm rolling or hot rolling) had more grain size than the Al-18Pb and Al-22Pb alloys.

Figs. 8(a)-8(c) represent SEM micrographs of semi-solid deposits of Al-18Pb, Al-22Pb alloys before and after warm rolling. Before warm rolling (Fig. 8(a)), Pb was settled down along the grain boundaries, and no cracks were found in both deposits (Al-18Pb and Al-22Pb). However, both Al-18Pb and Al-22Pb deposits showed more cracks with a higher percentage thickness reduction sample (60%). The formation of the pores over and inside the surface of the deposit depends upon the atomization process, in which molten metal rapidly converts into semi-solid droplets. Due to the warm rolling process, the shape of the Pb grains changes from globular to longitudinal. Microstructural features altered due to the turbulence behavior of the molten metal in warm rolling and spray deposition distance. Turbulence occurred due to the propagation of molten metal with high velocity, which led to the formation of pores over the surface of the deposit and alters the size of the grains. Pores cause multiple characterization defects which were minimized with the warm rolling process and nearly eliminated at higher thickness percentage reductions. All the cavities and pores were eliminated in both Al-18Pb and Al-22Pb deposits by using warm rolling process.

### 3.3. Porosity behavior

The porosity level is more in Al-22Pb than in Al-18Pb alloy due to higher Pb% before and after rolling also. The mechanism is explained as follows. The porosity level depends on melt percentage variation in spray. The deposition area of substrate increases rapidly from center to periphery due to the increase in radial distance. Therefore, the level of complexity to cover the entire substrate will increase from center to periphery. As deposit thickness increases, distance covered by droplets before deposition decreases. This results in increase in the liquid percentage in spray, leading to a decrease in porosity. The two types of porosities present in the samples before and after warm rolling are (i) cast porosity and (ii) crack porosity. The variations of porosity in peripheral regions of deposits with the increase percentage thickness reduction for various passes are represented in Fig. 9. Before warm rolling, both the deposits had casting porosity due to gas entrapment occurring in the rapid solidification of molten metal.

Before warm rolling, Al-18Pb alloy showed lower porosity and smeared surface than Al-22Pb alloy due to higher percentage of Pb. The levels of porosity in Al-18Pb and Al-22Pb were lower than the spray deposited Al-Si-Pb [16] due to higher percentage of Pb and absence of Si.

### 3.4. Hardness

Fig. 10 shows that the hardness of both deposits (Al-18Pb and Al-22Pb) increases with the rolling percentage increased up to 60%. This is mainly because at optimum distance of substrate from the nozzle, 15–30% liquid metal droplets first reach a good preform. If the distance between nozzle and substrate is more than the optimum distance, the liquid metal reaching the substrate is very low and, thus, would not give a proper cohesive property. As a result, the hardness value will decrease. At lower distance, high liquid content gives rise to a higher spray enthalpy at the surface of preform. So additional time is required to liberate this enthalpy, which causes coarsening of grains in the preform. As a result, only fewer droplets reach the substrate as finer grain leading to a decrease in hardness values.

Variation of hardness values related to a decrease in percentage thickness is shown in Fig. 10. Hardness values indirectly depend upon the percentage of porosity as higher percentages impart brittle nature to the materials. Before

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**Fig. 9** Variation of porosity vs. rolling passes or thickness reduction percentage.

**Fig. 10** Variation of hardness vs. rolling passes or thickness reduction percentage.
warm rolling, spray deposits of Al-18Pb has more hard than the Al-22Pb alloy due to the presence of cavities. In warm rolled deposits, both Al-18Pb and Al-22Pb alloys increased in percentage of thickness, resulting in an increase in hardness values compared to the casted spray deposits. Also, hardness values are lower for Al-22Pb alloy than for the Al-18Pb alloy; in general, it is reverse with respect to porosity comparison.

3.5. Wear characteristics

The wear rate with respect to the sliding speed at a fixed load of 4 kg for warm rolled deposits Al-18Pb and Al-22Pb is represented in Fig. 11(a). The wear rate decreases at a faster rate when the sliding speed is increased up to 0.85 m/s for both alloys. After that, the decrease in wear rate slows down gradually with the increase in sliding speed. The wear rate is lower for Al-18Pb alloy than for Al-22Pb alloy. The presence of higher Pb percentage in the Al-22Pb alloy resulted in the formation of the oxide layer over the surface of the deposit, causing the smearing effect. Due to smearing, pores were developed on the top portion of the specimens, which increased wear rate.

The relationship between sliding velocity and the coefficient of friction (μ) at a constant load of 5 kg for warm rolled deposits Al-18Pb and Al-22Pb is represented in Fig. 11(b). For initial increase up to 20 m/s, the μ value increased linearly. Further increments in sliding velocity up to 30 m/s resulted in a decrease in μ value. For the sliding velocity values above 30 m/s, the frictional coefficient value was in the increasing mode. In general, the frictional coefficient (μ) was constant with sliding velocity [16–20] in metals and alloys. In this research, Pb was used along with Al as Pb is a soft material and has lower crystallization temperature. The Al-22Pb alloy possess low hardness values, which resulted in higher wear rate and coefficient of friction when compared with Al-18Pb due to the higher % of Pb in the alloy composition. Fig. 11(c) represents the graph of weight loss vs. sliding distance with the load of 5 kg and sliding speed of 0.85 m/s. The weight loss increased linearly with sliding distance. The weight loss was more in Al-18Pb alloy than in Al-22Pb analog. As a linear context trend was achieved at 1500 m of sliding distance, the distance is important to investigate load variations with wear rate.

4. Conclusions

1. The Gaussian or Bell shape was obtained with Al-18Pb and Al-22Pb alloys at the following optimized conditions: pres-
sure of 10 bar, spray deposition distance of 42.3 cm, delivery tube diameter of 4 mm, and rotor inclination angle of 0°.

2 Only cast porosity was observed before warm rolling, however, both crack and cast porosity were observed after warm rolling in passes up to 1-3. At higher thickness reduction in 4th pass, both types of porosities were completely eliminated.

3 SEM images showed that the level of porosity in warm rolled deposits was significantly lower than the corresponding ones in cast spray deposits. With 60% thickness reduction samples, cavity and casting porosities were completely eliminated.

4 After warm rolling, the shape of the grain changed from globular to the ligament shape. At 60% thickness reduction, both alloys showed only 2% variation in total porosity.

5 Before warm rolling, hardness was higher in Al-18Pb alloy than in Al-22Pb alloy. After warm rolling, the hardness values improved in both alloys.

6 After warm rolling in Al-18Pb alloy, the coefficient of friction decreased with sliding velocity of 20 m/s, whereas in Al-22Pb alloy, the coefficient friction increased under the same conditions. This can be reasoned from higher % Pb in the latter.

Conflicts of interest

The authors declare no conflicts of interest.

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