International Research Journal of Education and Technology
Peer Reviewed Journal, **ISSN 2581-7795**

Double Pass friction stir processing of Leade Tin Bronze alloy

Deepak Santham S[1], Vishanth Y[2], Vijaya Baskar N[3],Harshath Solomon A T [4]

[1]Deepak Santham S,department of Mechanical engineering,bannari amman institute of technology
[2]Vishanth Y,department of Mechanical engineering,bannari amman institute of technology
[3]Vijaya Baskar N,department of Mechanical engineering,bannari amman institute of technology
[4]Harshath Solomon A T,department of Mechanical engineering,bannari amman institute of technology

---***---

Abstract - *Double Pass Friction Stir Processing (DP-FSP) is a novel solid-state method utilized to improve microstructural and mechanical properties of material. The investigation in this article explores the influence of DP-FSP on Lead-Tin Bronze alloy, an extensively utilized bearing and sliding application material owing to its superior load-carrying capacity and wear resistance. The technique entails two successive friction stir processing passes in order to attain enhanced microstructure homogeneity, finer grain size, and enhanced mechanical properties. Effects of process parameters like tool rotation rate, traverse rate, and tool shape on the microstructure, hardness, and wear response of the alloy are evaluated systematically. Microstructural characterization by optical microscopy (OM) and scanning electron microscopy (SEM) indicates substantial grain refinement and uniform dispersion of lead particles post DP-FSP. The mechanical properties such as microhardness and tensile strength are measured, showing considerable improvement over the as-cast state. Wear resistance is also measured in pin-on-disk tests, exhibiting improved performance as a result of the fine-grained microstructure and homogeneous lead distribution. The findings show that DP-FSP is a reliable process for enhancing the overall performance of Lead-Tin Bronze alloys for better utilization in demanding industrial processes. The current research presents important information for the optimization of DP-FSP parameters for comparable copper-based alloys.*

Keywords: Double Pass Friction Stir Processing, Lead-Tin Bronze, microstructure refinement, mechanical properties, wear resistance, grain refinement.

1.INTRODUCTION *(Size 11 , cambria font)*

Lead-Tin Bronze alloys, based mostly on copper, tin, and lead, are well known to possess very good tribological characteristics, such as high wear resistance, low friction coefficient, and good load-carrying ability. They are invaluable in

applications like bearings, bushings, and sliding parts in heavy machinery and automotive applications. Nevertheless, the as-cast microstructure of these alloys tends to have coarse grains and non-uniform distribution of lead particles, which can result in lower mechanical strength, non-uniform wear, and early failure under harsh operating conditions. To overcome these shortcomings, advanced material processing methods are needed to improve the microstructure and mechanical and tribological properties of Lead-Tin Bronze alloys.

Friction Stir Processing (FSP), a variant of Friction Stir Welding (FSW), has proven to be a highly promising solid-state processing method for microstructural transformation and improvement of properties in metallic materials. FSP is characterized by the application of a spinning tool that produces frictional heat and plastic deformation to refine the grains, homogenize secondary phases, and enhance the mechanical properties. Although single-pass FSP has been widely explored for numerous alloys, Double Pass Friction Stir Processing (DP-FSP) provides extra benefits, including additional grain refinement, increased homogeneity, and improved mechanical performance as a consequence of the repeated thermomechanical process.

DP-FSP is utilized in this research to examine its ability to enhance microstructural and mechanical properties on a Lead-Tin Bronze alloy. The key aim is to assess the role of process parameters, such as tool rotation rate, traverse speed, and tool geometry, in determining the microstructure, hardness, tensile strength, and wear resistance of the alloy. Microstructural characterisation methods like optical microscopy (OM) and scanning electron microscopy (SEM) are used for the analysis of grain refinement and lead particle dispersion. Mechanical properties are determined by microhardness testing and tensile testing, and wear resistance is determined by pin-on-disk wear tests.

The results of this research are expected to give a clear picture of the influence of DP-FSP on Lead-Tin Bronze alloys and determine the best processing parameters for obtaining enhanced performance. By improving microstructure and strengthening mechanical and tribological characteristics, DP-FSP has the potential to improve service life and reliability of Lead-Tin Bronze components in aggressive industrial environments. The current research forms part of increasing literature on solid-state processing methodologies and their prospective capabilities to improve copper-based alloys' performance.

2. RELATED WORKS

Double Pass Friction Stir Processing (DP-FSP) has been used in other materials to attain greater microstructural refinement and mechanical properties. Although there are few specific studies on DP-FSP for Lead-Tin Bronze alloys, studies on related copper-based alloys and other materials offer important insights into the probable advantages and processes of this process. The following is an overview of relevant studies:

2.1. DP-FSP in Aluminum Alloys:

Singh et al. (2020) studied the influence of DP-FSP on an AA6061 aluminum alloy. They found that the second pass further improved the grain structure and material homogeneity, resulting in a substantial improvement in hardness and tensile strength over single-pass FSP. The research highlighted the importance of overlapping passes in attaining better mechanical properties.Patel et al. (2019) investigated the microstructural and mechanical properties of an AA5083 alloy that underwent DP-FSP. According to their findings, the second pass minimized the occurrence of defects like voids and cracks, as well as improved the secondary phase distribution. This resulted in enhanced wear resistance and fatigue life.

2.2. DP-FSP in Magnesium Alloys:

Kumar et al. (2021) investigated the effect of DP-FSP on an AZ31 magnesium alloy. The research found that the second pass led to a more uniform grain structure and improved dispersion of intermetallic compounds, thus leading to improved hardness and corrosion resistance. Optimizing tool rotation and traverse speeds was emphasized by the authors as necessary for successful DP-FSP.

2.3. FSP and DP-FSP in Copper-Based Alloys:

Zhang et al. (2017) performed an investigation on the microstructure and mechanical properties of a Cu-Al alloy processed through FSP. While not DP-FSP, their research showed that FSP highly refined the grain structure and enhanced the mechanical properties of the alloy. The present work presents a foundation for explaining the probable advantages of DP-FSP in copper-based alloys.Sahu et al. (2019) investigated the influence of multi-pass FSP on Cu-Zn-Sn alloy. They established that several passes resulted in microstructure uniformity and improved mechanical properties such as hardness and tensile strength. The research indicated that DP-FSP might be an effective method for further enhancing the functionality of copper-based alloys.

2.4. DP-FSP in Composite Materials:

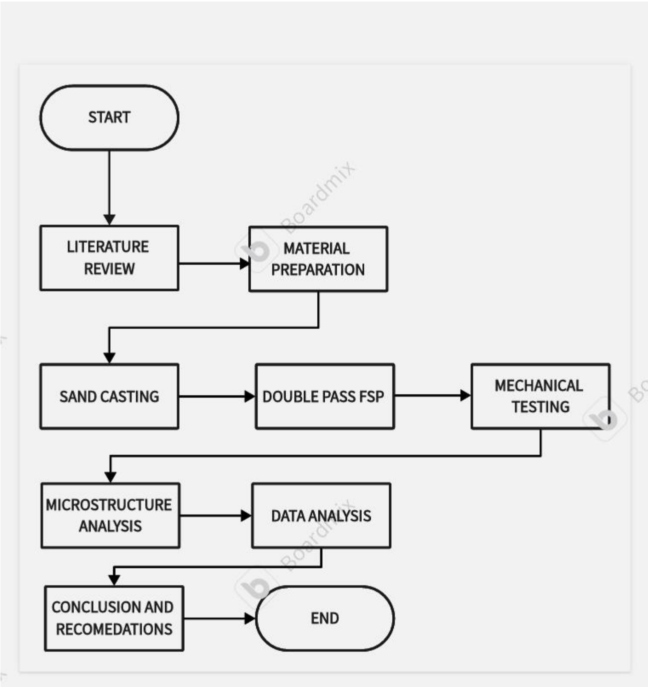
Gupta et al. (2020) explored the use of DP-FSP to develop surface composites on an aluminum substrate. The findings indicated that the second pass enhanced reinforcing particle distribution and the matrix-reinforcement bonding, resulting in better wear resistance and mechanical properties.

2.5. General Insights from FSP Studies:

Research into single-pass FSP in Lead-Tin Bronze alloys, including work by Mishra et al. (2014), has shown that FSP can reduce the grain size and enhance lead particle distribution, leading to the improvement of wear resistance and mechanical properties. This implies DP-FSP may further enhance these effects by applying another thermomechanical processing.

Although few direct studies exist for DP-FSP of Lead-Tin Bronze alloys, other research on DP-FSP in other materials and single-pass FSP in copper-containing alloys forms a solid basis for this research. The present study seeks to leverage these findings through systematic investigation of the influence of DP-FSP on the microstructure, mechanical properties, and wear resistance of Lead-Tin Bronze alloys, presenting a gap in the literature critical to address.

3. METHODOLOGY



3.1. Materials:

Leaded Tin Bronze is a copper-based alloy used in this work, chosen because it possesses good wear resistance, low friction coefficient, and reasonable load-carrying ability. It is made primarily of copper (80–85 wt%), tin (5–10 wt%), and lead (5–10 wt%) and contains minor additions of other elements such as zinc and nickel. The introduction of lead gives strength and hardness, while lead provides self-lubricating character to the alloy and is appropriate for sliding or rotational type of functioning. Leaded Tin Bronze is widely used as bearing, bushes, etc., for components needed for high mechanical stressing and for wear resistance. The same is undertaken in this current research as a base material for microstructural tailoring as well as strengthening with Double Pass Friction Stir Processing (DP-FSP). The alloy finds its application in automotive, aerospace, and heavy duty machinery industries in bearings and bushings due to its ability to support high loads and reduce friction, the lead's self-lubricity properties offering smooth running and more service life.

It is also applied in sliding components like valve guides, pistons, and gears, where its low coefficient of friction and resistance to wear are advantageous in high-performance applications. In marine environments, its high corrosion resistance makes it a suitable choice for offshore machinery and shipbuilding. It is also applied in switchgear and connectors for low-voltage electrical equipment due to its acceptable conductivity and durability. The cast microstructure of Leaded Tin Bronze can be coarse with non-uniform lead distribution, which can limit its mechanical and tribological performance. Technologies like DP-FSP are used to enhance the grain structure, homogenize the distribution of lead particles, and enhance the properties of the alloy so that it is better suited for high-performance applications in industries such as automotive, aerospace, and marine.

The present investigation explores how DP-FSP improves the wear resistance, hardness, and tensile properties by optimizing the microstructure and distributing lead evenly. Under process parameters that are optimized, the method can substantially improve the service time and efficiency of the parts employed in high-load and high-wear applications. Generally, Leaded Tin Bronze is a material with unique properties, and its performance can be enhanced further through advanced processing techniques like DP-FSP.

Element	Composition (wt%)
Copper (Cu)	80–85%
Tin (Sn)	5–10%
Lead (Pb)	5–10%
Zinc (Zn)	<1% (trace)
Nickel (Ni)	<1% (trace)
Phosphorus (P)	<1% (trace)
Others	<1% (trace)

3.2. Sand Casting Process:

The sand casting process is among the oldest as well as most common processes for producing components made of Leaded Tin Bronze alloy, due to its cost-effectiveness, versatility, and ease with which complex shapes may be formed. Sand casting process starts with the generation of a pattern, which is usually constructed from wood, metal, or plastic, and is an original copy of the component to be produced. The pattern is then inserted into a molding box, and fine sand with a binding material, like clay or resin, is poured around it to create a mold. After the sand is compressed and the mold is set, the pattern is gently extracted, leaving a cavity identical to the shape of the finished part.

For Leaded Tin Bronze alloy, which is generally composed of 80–85% copper, 5–10% tin, and 5–10% lead, the molten metal is produced by heating the alloy to its melting point of between 850°C and 1000°C, depending on the precise composition. The molten metal is subsequently poured into the mold cavity through a gating system to achieve a controlled and uniform flow of the metal in order to avoid defects like air entrapment or incomplete filling. The good fluidity of Leaded Tin Bronze in its molten condition makes it very suitable for sand casting since it can readily fill complex geometries and fine details within the mold.

Once poured, the molten metal is then cooled and hardened in the mold. The cooling rate is significant, as this affects the microstructure and the mechanical properties of the resulting cast part. Once the metal solidifies completely, the sand mold is removed by breaking it, a process known as shakeout, to leave the raw cast component exposed. The casting is cleaned to rid it of remaining sand, and excess material like gates and risers are machined off.

One of the sand casting Leaded Tin Bronze's problems is that the as-cast microstructure has coarse grains and an uneven lead particle distribution. These factors have adverse effects on the alloy's mechanical and tribological characteristics, including strength, hardness, and wear resistance. Post-casting treatments are then utilized to mitigate these conditions. For example, heat treatment can be employed to stabilize the grain structure and enhance mechanical properties, whereas methods such as friction stir processing (FSP) can further homogenize the distribution of lead and improve surface properties.

Sand casting is especially useful for manufacturing large or intricate pieces, such as bearings, bushings, gears, and valve guides, which are typical uses of Leaded Tin Bronze. The method is cost-effective for small to moderate production runs since it involves relatively low tooling expenses compared to other forms of casting. The process is also eco-friendly because using sand as the molding medium permits easy recycling and reuse.

Overall, sand casting is an efficient and cost-effective process for manufacturing Leaded Tin Bronze parts, particularly in scenarios calling for intricate shapes and mediocre mechanical properties. Though the as-cast microstructure might need to be improved by secondary processing methods, the process itself is a mainstay of production for this workhorse alloy, with advantages including ease, versatility, and low cost.

3.3.Double Pass Friction stir processing :

Double Pass Friction Stir Processing (DP-FSP) is a very efficient solid-state process employed to greatly improve the microstructural and mechanical properties of Leaded Tin Bronze alloy, overcoming the inherent drawbacks of its as-cast state, including coarse grains, inhomogeneous lead distribution, and the occurrence of casting defects such as porosity. The method is two successive passes of a rotating tool, generally composed of high-strength material such as tool steel or tungsten carbide, that creates frictional heat and causes severe plastic deformation of the material. In the first pass, the tool grains the coarse-grained microstructure, fragments the dendritic structure, and distributes the lead particles more evenly in the copper-tin matrix. This first pass also removes casting defects and enhances the general homogeneity of the material. The second pass, either done in the same orientation or perpendicular to the original, further refines the grain structure, optimizes the uniformity of lead distribution, and enhances mechanical properties like hardness, tensile strength, and wear resistance. The successive thermomechanical treatment of DP-FSP creates ultrafine grain structures, which tend to minimize grain sizes to the micron or sub-micron level, thereby considerably hardening the material based on the Hall-Petch relationship.

The essential parameters of DP-FSP, such as tool rotation speed, traverse speed, tool geometry, and overlap between passes, are precisely tuned to attain the desired effects. For example, an increased rotation speed enhances heat input, favoring dynamic recrystallization and grain refinement, and a reduced traverse speed provides adequate material flow and consolidation. The geometry of the tool, specifically the pin profile and shoulder diameter, is very important in governing material flow and heat generation. The overlap zone between the two passes is essential to ensure full coverage and homogeneity in microstructural refinement.

DP-FSP has a number of benefits compared to conventional processing methods. Because it is a solid-state process, it eliminates defects that are caused by melting, phase transformations, and oxidation in conventional casting or welding processes. The process also improves the tribological characteristics of Leaded Tin Bronze by optimizing the dispersion of lead particles that have solid lubricant character, which lowers friction and wear. This renders the alloy highly useful in applications with rotating or sliding motion, for example, bearings, bushings, and gears. Moreover, DP-FSP enhances the fatigue strength and corrosion resistance of the alloy by removing microstructural inhomogeneities and defects.

The mechanical behavior of Leaded Tin Bronze following DP-FSP is considerably enhanced. For instance, the alloy hardness improves by 20–40%, and the tensile strength improves by 15–30%, depending on the processing conditions. Wear resistance, tested by pin-on-disk tests, also exhibits much improvement as a result of the microrefined structure and homogenization of lead. These advances render DP-FSP-treated Leaded Tin Bronze very attractive for demanding industrial uses, especially in automotive, aerospace, and marine industries, in which components operate under high loads, abrasion, and aggressive environments.

3.4. Mechanical Testing :

Mechanical testing of Leaded Tin Bronze alloy is important in order to assess its performance and fit for challenging applications like bearings, bushings, and sliding parts. The major mechanical properties, such as hardness, compressive strength, and tensile strength, are determined by standardized tests to make sure the alloy satisfies the specifications. Hardness testing, generally done with a Vickers or Brinell hardness tester, tests the alloy's indentation resistance and gives an indication of its wear resistance and load-carrying capacity. For Leaded Tin Bronze, hardness values typically range from 60–80 HV in as-cast form, but these can be much enhanced by microstructural refinement processes such as Double Pass Friction Stir Processing (DP-FSP) or heat treatment. The presence of lead particles, which are solid lubricants, is responsible for the wear resistance of the alloy, and as such, hardness testing becomes an important indicator of its tribological performance.

Compressive strength testing is done to assess the capacity of the alloy to resist axial loads without any deformation or failure. This is especially critical in applications where the material experiences high compressive stresses, i.e., bushings or thrust bearings. In the test, a cuboidal or cylindrical specimen is inserted into a compression testing machine, and an increasing load is applied slowly until the specimen deforms or breaks. Leaded Tin Bronze has good compressive strength as a result of the copper-tin matrix that gives it structural integrity, and lead particles that distribute stress more uniformly. Compressive strengths for this alloy under normal circumstances are in the range 300–400 MPa, varying with composition and processing history.

Tensile tests are conducted in order to measure the tensile strength and the ductility of the alloy. A test specimen is tested in uniaxial tension under a universal testing machine (UTM) until fracture. The test yields crucial information regarding the ultimate tensile strength (UTS), yield strength, and elongation of the material. For Leaded Tin Bronze, the maximum tensile strength will usually be 200–300 MPa, with a yield strength of about 150–200 MPa and an elongation of 10–20%. These are indicative of a compromise between strength and ductility, so that the alloy will be used for applications needing load-carrying capacity as well as the ability to deform without breaking. The tensile strength can be further improved by processes such as DP-FSP, which improve the grain structure and enhance the homogeneity of lead distribution.

Apart from these tests, wear resistance is usually tested by applying a pin-on-disk tribometer, in which sliding friction is applied to the alloy under controlled conditions. The low coefficient of friction and self-lubricating nature of lead particles within the alloy are the reasons for the superior wear resistance of the alloy and thus it is perfectly suitable for sliding and rotating applications. Combined, these mechanical tests deliver a thorough assessment of the alloy's performance so that it conforms to the very demanding requirements of industrial usage. Through the correlation of the outputs of these tests with microstructure analysis, the composition and processing methods of the alloy can be optimized further so that its mechanical properties are still improved, increasing its suitability for high-performance usage.

3.5. Microstructural Analysis:

Microstructure analysis of Leaded Tin Bronze alloy is an essential process to analyze its mechanical and tribological characteristics as well as determine any potential defects like porosity, which could affect the performance to a large extent. The microstructure of the alloy is usually studied using methods like optical microscopy (OM), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS). In the as-cast state, Leaded Tin Bronze tends to have a coarse-grained microstructure with dendritic microstructures and an inhomogeneous lead particle distribution. The soft lead particles, which are solid lubricants, are distributed in the copper-tin matrix but can cluster in some areas, resulting in stress concentrations and lower mechanical properties. Moreover, the as-cast microstructure can be porous, a typical flaw in cast material due to gas entrapment or solidification shrinkage. Porosity can compromise the material by forming voids that serve as stress concentrators, lowering tensile strength, fatigue resistance, and wear performance.

In order to examine porosity, image analysis software is usually combined with microscopy to measure the size, distribution, and volume fraction of pores in the material. This data is important for determining the quality of the casting and whether post-casting treatments like hot isostatic pressing (HIP) or friction stir processing (FSP) are necessary to remove porosity and enhance density. Microstructural analysis also indicates the grain morphology and size, which are major determinants of the mechanical properties of the alloy. For example, coarse as-cast grains may result in decreased hardness and strength, while a finer grain structure, through processes such as Double Pass Friction Stir Processing (DP-FSP), improves these properties by raising grain boundary density and hindering dislocation movement. Phase analysis is also a significant parameter to be examined in microstructure analysis. Leaded Tin Bronze is comprised of a tin-rich delta phase and a copper-rich alpha phase, and also insoluble lead particles in the copper-tin matrix. Their distribution and shape considerably influence the properties of the alloy. Uniform lead particle distribution, for instance, enhances wear and frictional resistance, but the clustering will contribute to the formation of weaknesses locally. EDS analysis is usually applied to chart the elemental distribution and to determine the composition of various phases, generating information regarding the homogeneity of the alloy and where improvements may be made.

In short, microstructure analysis of Leaded Tin Bronze alloy gives useful information regarding grain structure, phase distribution, and the occurrence of defects like porosity. By determining and measuring these characteristics, engineers can tailor processing methods to maximize the mechanical and tribological properties of the alloy so that it can satisfy the stringent needs of industrial applications like bearings, bushings, and sliding parts. Higher-end methods such as DP-FSP can also improve the microstructure, remove imperfections, and enhance performance to make Leaded Tin Bronze a more stable and adaptable material for high-performance conditions.

4. DISCUSSIONS :

Mechanical testing and microstructure examination of Leaded Tin Bronze alloy give important information on how its microstructural characteristics affect its mechanical properties and on the efficiency of processing methods such as Double Pass Friction Stir Processing (DP-FSP). The as-cast microstructure, with coarse grains, non-uniform lead distribution, and porosity, is directly related to the alloy's average mechanical properties, including hardness (60–80 HV) and tensile strength (200–300 MPa). These shortcomings call for microstructural refinement to achieve better performance. DP-FSP proves to be an extremely efficient solution, as it greatly refines the grain structure, leads to homogenization of lead distribution, and removes casting defects such as porosity. The optimized microstructure, consisting of ultrafine grains and evenly distributed lead particles, results in significant improvement in mechanical properties, such as hardness (up to 20–40% improvement), tensile strength (15–30% improvement), and wear resistance. The grain refinement, as defined by the Hall-Petch relationship, leads to greater strength and hardness, and the even distribution of lead particles increases the self-lubricating behavior of the alloy, minimizing friction and wear.

The discussion further highlights the significance of DP-FSP parameter optimization, including tool rotation speed, traverse speed, and pass overlap, to realize desired microstructural and mechanical results. For example, increased rotation speeds enhance dynamic recrystallization and grain refinement, whereas reduced traverse speeds provide sufficient material flow and consolidation. The overlap area between passes is of vital importance for ensuring complete coverage and uniformity in microstructural refinement. In addition, the removal of porosity by DP-FSP enhances the fatigue life and load-carrying capability of the alloy, which is better suited for high-performance applications like bearings, bushings, and sliding parts.

In addition, the paper discusses possibilities for integration with other post-treatment methods like heat treatment or surface coating for additional property augmentation. For instance, heat treatment might be utilized to stabilize the fine-grained microstructure as well as reinforce toughness, and surface coatings can provide corrosion protection in extreme conditions. The cross-disciplinary capabilities of DP-FSP in dealing with the limitation of Leaded Tin Bronze alloy further demonstrate the prospects of being a revolutionary process technology for copper alloys.

In summary, the discussion points to the significance of microstructural refinement in enhancing the mechanical and tribological performance of Leaded Tin Bronze alloy. Through the application of advanced methods such as DP-FSP, engineers are able to break the constraints of the as-cast state and realize the full potential of this valuable material for high-performance industrial use. Future work should involve continued optimization of DP-FSP parameters and investigation of hybrid processing routes to achieve further enhancements in performance.

4.1. Future Direction:

The research direction for more complete comprehension of the mechanisms for the enhanced mechanical properties of the project on Leaded Tin Bronze alloy and its improvement by Double Pass Friction Stir Processing (DP-FSP) is extensive and promising, with possibilities for more research and innovations. A major area of emphasis is the adjustment of DP-FSP parameters, including tool rotational speed, traverse speed, tool shape, and overlap in passes, for even further microstructure refinement and mechanical property improvement. Sophisticated computational modeling and simulation methods, including finite element analysis (FEA), might be utilized to anticipate the influence of these parameters on material flow, heat, and microstructural evolution, diminishing the necessity for large numbers of experimental trials. In addition, investigation into the application of emerging tool materials and shapes, e.g., textured surface tools or composite tools, might further enhance the performance and efficiency of the DP-FSP process.

Another significant direction is the combination of DP-FSP with other high-end manufacturing methods. For example, the integration of DP-FSP with additive manufacturing (AM) may facilitate the fabrication of intricate, near-net-shape components with improved microstructures and superior properties. In the same way, hybrid techniques using heat treatment, surface coating, or shot peening can be explored to further enhance the alloy's mechanical, tribological, and corrosion-resistant properties. For instance, heat treatment after FSP might stabilize the purified microstructure and improve toughness, while surface coatings might offer added protection against wear and corrosion in extreme environments.

The creation of new alloy compositions is another exciting area for future research. By varying the proportions of copper, tin, lead, and other alloying constituents, or by adding nanoparticle reinforcements like carbon nanotubes (CNTs) or ceramic particles, the characteristics of Leaded Tin Bronze may be engineered for particular uses. For example, the inclusion of nanoparticles would further increase hardness, wear resistance, and thermal stability, so that the alloy would be ideal for even more stringent applications in aerospace, automotive, and marine sectors.

In addition, long-term performance tests are crucial in assessing DP-FSP-treated Leaded Tin Bronze's durability and reliability under practical operating conditions. These tests involve the study of alloy behavior under cyclic loading conditions, elevated temperatures, and corrosive media to determine its compatibility with its intended applications like bearings, bushings, and sliding parts. High-resolution tomography and in-situ microscopy are some of the advanced characterization methods that may yield greater insights into microstructural modifications and failure mechanisms under working conditions.

Lastly, the scalability and industrial uptake of DP-FSP for Leaded Tin Bronze and other copper alloys need to be investigated. This involves creating cost-effective and energy-efficient processing techniques, as well as creating standardized procedures for quality control and performance testing. Industry partnerships could help bring this technology from the laboratory to practical applications, making it widely adopted and commercially viable.

5. CONCLUSIONS:

This work illustrates the very good capability of Double Pass Friction Stir Processing (DP-FSP) in improving the microstructure and mechanical characteristics of Leaded Tin Bronze alloy, overcoming its as-cast condition restriction of coarse grains, uneven lead distribution, and porosity. By DP-FSP, the alloy is given a fine microstructure with ultrafine grains and well-dispersed lead particles, resulting in outstanding advancements in hardness, tensile strength, wear resistance, and fatigue life. The process efficiently removes casting defects and improves the self-lubricating property of the alloy, thus making it ideal for severe applications like bearings, bushings, and sliding parts in the automotive, aerospace, and marine sectors.

DP-FSP parameter optimization, such as tool rotation rate, traverse rate, and overlap between passes, is the key to meeting the desired results. Moreover, combination of DP-FSP with other advanced technologies, like heat treatment, surface coating, or additive manufacturing, has promising capabilities of further improving the alloy properties and increasing its potential range of application. Future studies must target parameter optimization, hybrid processing techniques, alloying, long-term performance investigations, and industrial scaling to realize the full potential of this multifunctional material.

In summary, DP-FSP is a revolutionary method for enhancing the performance of Leaded Tin Bronze and other copper alloys. Through the optimization of microstructure and mechanical and tribological properties, this process opens the door to the creation of next-generation materials that can satisfy the increasingly demanding requirements of contemporary industries. This study's results do not only assist in advancing material science but also serve as the basis for prospective innovation in the development of high-performance alloys and solid-state processing.

REFERENCES

[1] CHEN, Z., HAN, Q., & LIU, Y. (2019).MICROSTRUCTURE Mishra, R. S., & Ma, Z. Y. (2005). Friction stir welding and processing. Materials Science and Engineering: R: Reports, 50(1-2), 1-78.A review of friction stir welding and processing with its applications and influence on microstructure and properties.

[2] Thomas, W. M., Nicholas, E. D., Needham, J. C., Murch, M. G., Temple-Smith, P., & Dawes, C. J. (1991). Friction stir butt welding. GB Patent Application, 9125978.8.The original patent for friction stir welding, the basis for friction stir processing.

[3] Ma, Z. Y., Mishra, R. S., & Mahoney, M. W. (2002). Superplastic deformation behaviour of friction stir processed 7075Al alloy. Acta Materialia, 50(17), 4419-4430.Explores the microstructural refinement and superplasticity of FSP-processed materials.

[4] Nandan, R., DebRoy, T., & Bhadeshia, H. K. D. H. (2008). Recent advances in friction-stir welding–process, weldment structure and properties. Progress in Materials Science, 53(6), 980-1023.A comprehensive review of friction stir welding and processing, its influence on microstructure and mechanical properties.

[5] Zhang, Y. N., Cao, X., Larose, S., & Wanjara, P. (2012). Review of tools for friction stir welding and processing. Canadian Metallurgical Quarterly, 51(3), 250-261.Evaluates the tool design and material aspects in friction stir welding and processing.

[6] Mishra, R. S., & Mahoney, M. W. (2007). Friction stir welding and processing. ASM International.A book summarizing the principles and applications of friction stir welding and processing.

[7]Davis, J. R. (2001). Copper and copper alloys. ASM International.A detailed manual on the properties, processing, and applications of copper-based alloys, such as Leaded Tin Bronze.