

CONSIDERATIONS REGARDING DEFECTS THAT MAY OCCUR DURING FSP/SFSP PROCESSING OF ALUMINUM ALLOYS

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ABSTRACT: The paper provides a comprehensive analysis of the defect phenomena associated with friction stir processing (FSP) and submerged friction stir processing (SFSP) of aluminium alloys. The investigation systematically addresses the origins, typologies, and implications of both surface and internal defects observed in rolled and cast aluminium alloys subjected to these advanced solid-state processing techniques. Key factors influencing defect formation, including tool geometry, process parameters, intrinsic material characteristics, and environmental conditions, are critically examined. The review further delineates material-specific responses to FSP/SFSP and highlights the challenges posed by initial microstructural inhomogeneities and compositional variations. Strategies for defect prevention are discussed, emphasizing the importance of optimized tool design, precise process control, and the integration of post-processing treatments. The findings underscore the necessity of a multidisciplinary approach - encompassing rigorous material pre-characterization, controlled processing environments, and adaptive monitoring systems - to ensure structural integrity and enhanced mechanical performance of processed components. This work advances the understanding of defect mechanisms in FSP/SFSP and offers evidence-based guidelines for the production of high-quality, high-performance aluminium alloy components suitable for demanding engineering applications.

KEYWORDS: FSP, SFSP, causes of defects, rolled aluminium alloys, cast aluminium alloys

1. INTRODUCTION

Friction Stir Processing (FSP) represents an advanced solid-state technique for modifying the microstructure of aluminium alloys [1]. This process has demonstrated significant potential in enhancing the mechanical and physical properties of aluminium alloys, thereby broadening their applicability in high-performance engineering sectors. Unlike conventional processing routes, FSP achieves microstructural refinement and property improvement without inducing a phase change by melting [2].

The methodology involves the use of a rotating tool equipped with a specifically designed pin, which is plunged into the substrate material. The resulting frictional interaction generates localized heat, sufficient to induce plasticization of the material while maintaining its solid-state condition [3].

The FSP process steps:

- tool design: the tool employed in FSP typically comprises a cylindrical shoulder and a pin, with specific geometric configurations selected according to the intended microstructural and mechanical property enhancements;
- workpiece preparation: the aluminium alloy specimen is rigidly secured in place to ensure positional stability, and the FSP tool is accurately aligned with the targeted processing zone;
- material processing: during FSP, the tool undergoes high-speed rotation and traverses the surface of the workpiece. The frictional interaction between the tool and the material produces localized thermal energy, elevating the temperature sufficiently to induce plasticization and facilitate material flow around the pin without reaching the melting point;
- post-processing cooling: as the tool advances along the workpiece, the locally heated region undergoes subsequent cooling and solidification, resulting in a homogenized and refined microstructure.

Benefits of FSP [4]:

- grain refinement: FSP can significantly reduce grain size, enhancing mechanical properties like strength and toughness;
- improved microstructure: the process can eliminate defects such as voids and inclusions in the material;
- enhanced properties: FSP - treated aluminium alloys often exhibit improved wear resistance, corrosion resistance, and fatigue life;
- versatility: this technique can be applied to various aluminium alloys and can be adapted for different applications.

Applications [5]:

- aerospace: FSP is used to enhance the performance of components subjected to high strength and lightweight requirements;

- automotive: improved mechanical properties make FSP-treated aluminium suitable for structural components that require weight reduction;
- marine: enhanced corrosion resistance is beneficial for marine applications;
- consumer electronics: FSP can improve the properties of aluminium used in electronic housings and components.

Submerged Friction Stir Processing (SFSP) is a comparatively new variation of the standard FSP method. [6]. Both methods involve a non-consumable rotating tool that is inserted into a workpiece and rotated at high-speed while being fed along a pre-determined path. However, SFSP differs from FSP by being conducted in a controlled submerged environment, typically a liquid bath.

Advantages of SFSP over FSP [7]:

- improved surface finish: the submerged environment helps to dissipate heat more effectively, leading to a smoother and more refined surface finish;
- enhanced material properties: SFSP can induce significant microstructural changes, such as grain refinement and the formation of specific phases, which can improve mechanical properties like hardness, strength, and ductility;
- reduced oxidation and contamination: the submerged environment minimizes exposure to air, reducing oxidation and contamination of the processed surface;
- potential for novel material processing: SFSP can be used to create unique microstructures and properties that are difficult or impossible to achieve with traditional FSP or other processing techniques.

Applications of SFSP in aluminium alloys [8]:

- surface modification: Improving surface hardness, wear resistance, and corrosion resistance;
- joining of dissimilar materials: creating strong and durable joints between different aluminium alloys or between aluminium and other materials;
- repair of damaged components: repairing defects like cracks and porosity in aluminium components;
- manufacturing of functional gradients: creating materials with varying properties across their thickness, such as graded hardness or corrosion resistance.

2. TYPES OF DEFECTS IN FSP/SFSP

FSP and SFSP are advanced manufacturing techniques that can significantly improve the mechanical properties of aluminium alloys. However, like any manufacturing process, they can introduce defects [9].

Some common types of defects observed in FSP/SFSP for rolled and cast aluminium alloys are:

2.1. Common defects

- *Surface defects* (figure 1):
  - flash: excess material extruded from the edges of the processed zone, often caused by excessive heat input or improper tool geometry (figure 1a);
  - tool mark: indentations left on the surface by the tool, particularly noticeable with improper tool feed or rotational speed (figure 1b);
  - surface cracks: small cracks that can form on the surface due to excessive thermal stresses or poor tool design (figure 1c).

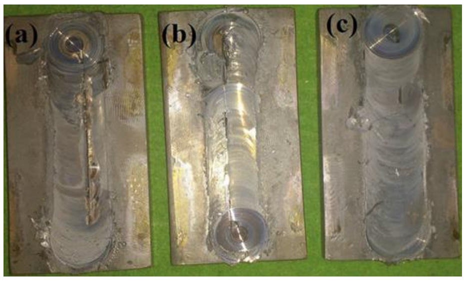

Figure 1. Surface defects in FSP/SFSP, [10]

(a) flash, (b) tool mark, (c) surface cracks

- *Internal defects* (figure 2):
  - voids and porosity: small cavities within the material, often caused by trapped gas or inadequate material flow (figure 2a);
  - inclusions: foreign particles embedded in the material, which can originate from tool wear or contamination during processing (figure 2b);
  - unwelded zones: regions where the material has not been fully consolidated, leading to reduced strength and integrity (figure 2c);
  - texture;
  - development: preferential orientation of grains, which can negatively impact mechanical properties, especially ductility (figure 2d).

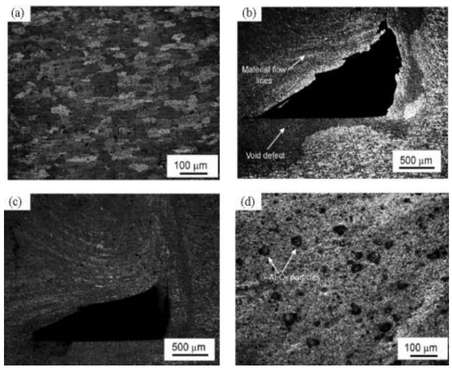

Figure 2. Internal defects in FSP/SFSP, [11]

(a) voids and porosity, (b) inclusions, (c) unwelded zones, (d) texture development

2.2. Specific considerations for rolled and cast alloys

- *Rolled aluminium alloys*:
  - texture modification: FSP/SFSP can modify the existing texture of rolled alloys, which can impact their mechanical properties [12];
  - residual stresses: the process can introduce residual stresses, which may affect the long-term performance of the material [13].

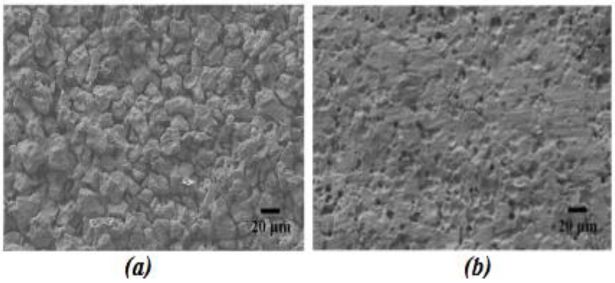

Figure 3. Microstructure of the base material and the processed aluminium alloy, [12]

(a) base specimen, SEM image, (b) FSP processed sample after IGC test

- *Cast aluminium alloys*:
  - porosity: cast alloys often contain porosity, which can be exacerbated by improper FSP/SFSP parameters [13];
  - segregation: inhomogeneous distribution of alloying elements can lead to variations in mechanical properties within the processed zone [14];
  - microstructural inhomogeneity: the initial microstructure of cast alloys can influence the final microstructure after FSP/SFSP, potentially leading to defects [15].

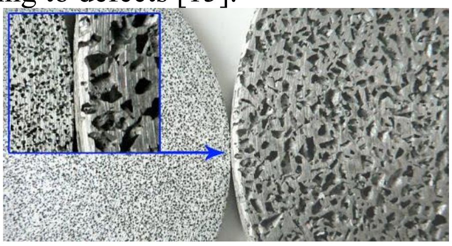

Figure 4. Porosity in aluminium alloy die castings, [13]

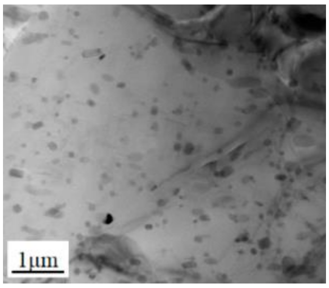

Figure 5. The microstructural inhomogeneity grain phase distribution of cast aluminium alloy, [15]

Minimizing defects in FSP/SFSP, careful process parameter selection and optimization are very important. Key factors to consider include [16]:

- tool design: proper tool geometry, including pin profile and shoulder diameter, can significantly impact defect formation;
- process parameters: optimal settings for rotational speed, feed rate, and tool plunge depth are essential;
- material properties: the initial microstructure and mechanical properties of the material influence the defect formation;
- submerged environment (SFSP): the choice of the submerging medium and its temperature can affect the defect formation.

By precisely controlling these parameters, it is feasible to manufacture high-quality aluminium alloy components via FSP/SFSP, which exhibit improved mechanical properties [17].

3. CAUSES OF THE OCCURRENCE OF DEFECTS IN FSP/SFSP

The occurrence of defects during FSP and SFSP is governed by a multifaceted interaction among tool geometry, processing parameters, intrinsic material characteristics, and ambient conditions. A thorough elucidation of these contributory factors is essential for the optimization of process variables and the reliable fabrication of aluminium alloy components with superior quality standards.

3.1. Tool design and geometry

- *Pin and shoulder geometry:* the configuration of both the pin and shoulder is fundamental in modulating thermal input and material flow characteristics during friction stir processing. Suboptimal tool geometries can lead to uneven material stirring, resulting in localized overheating, incomplete plasticization, and the emergence of defects such as voids, tunnels, or unwelded regions [18]. Furthermore, excessively aggressive tool designs may facilitate surplus material expulsion, often observed as flash along the processed boundaries;
- *Tool degradation:* progressive tool wear and surface deterioration alter the effective geometry and surface condition with continued use. These modifications can adversely affect heat generation consistency, promote contamination from wear debris, and increase the likelihood of inclusions and microstructural heterogeneities within the processed region [19].

3.2. Process parameters

- *Rotational and traverse speeds:* the rotational velocity of the tool is a primary determinant of frictional heat generation, while traverse speed dictates the duration of thermal exposure at any given point. Excessive rotational speeds can cause overheating and excessive material softening, frequently leading to flash formation. Conversely, insufficient speeds may result in inadequate softening, facilitating the formation of voids and incomplete metallurgical bonding [20];

- *Tool plunge depth*: precise regulation of the plunge depth is essential to ensure full penetration and adequate material mixing throughout the thickness of the workpiece. Deviations from optimal plunge parameters may produce regions of incomplete consolidation (commonly referred to as kissing bonds) or induce local thermal gradients that exacerbate defect formation;
- *Dynamic process stability*: variability in processing parameters - arising from equipment fluctuations or transient environmental conditions - can cause significant alterations in localized thermal and mechanical environments. These dynamic variations may induce non-uniform strain and temperature distributions, further increasing the risk of defect generation [21].

3.3. Material properties

- *Initial microstructure:* the microstructural state of the aluminium alloy prior to processing has a substantial influence on its response to FSP/SFSP. For example, cast alloys typically exhibit inherent porosity and compositional segregation, which may act as nucleation sites for defects. Rolled alloys, on the other hand, may display anisotropic behaviour due to directional grain structures, with processing-induced changes either enhancing or compromising their mechanical properties [22];
- *Chemical composition and inhomogeneities*: variations in alloying element distribution can affect both thermal conductivity and melting behaviour. Such chemical inhomogeneities may cause uneven heat distribution, promoting the development of inclusions, segregation bands, or other microstructural discontinuities within the processed zone.

3.4. Environmental conditions

- *Ambient temperature and humidity: e*xternal environmental parameters, including ambient temperature and humidity, are critical in managing the thermal profile of the FSP/SFSP process. Variations in these factors can impact cooling rates and solidification dynamics. Lower ambient temperatures may induce rapid quenching, potentially increasing residual stress, while elevated temperatures can delay cooling, thereby extending the period during which defects may form;
- *Submerging medium in SFSP:* the characteristics of the submerging medium - such as temperature, specific heat, and thermal conductivity - are pivotal for achieving uniform cooling. An inadequately controlled submerging environment can promote uneven thermal gradients, facilitating the development of residual stresses, abnormal grain growth, and increased defect incidence [23].

3.5. Synergistic interactions

The aforementioned factors rarely act independently; rather, their combined effects often intensify the propensity for defect formation. For example:

- *Tool - process parameter interactions:* inappropriate tool geometry may amplify the detrimental impact of unstable processing parameters, resulting in compounded thermal and mechanical fluctuations;
- *Material - environment interactions:* intrinsic material defects, such as those prevalent in cast alloys, may be exacerbated by adverse environmental conditions, leading to an increased defect rate and reduced component performance;
- *Feedback mechanisms:* pre-existing microstructural imperfections can generate localized instabilities in heat generation and material flow, which may propagate and escalate through feedback effects during processing.

4. PREVENTION/AVOIDANCE OF DEFECTS

The realization of defect-free aluminium alloy components via FSP and SFSP necessitates a comprehensive strategy that addresses the root causes of defect formation and incorporates both preventative and corrective methodologies. The following sections outline evidence-based practices for defect control, supported by current literature.

4.1. Environmental factors

A key aspect of defect minimization consists of the deliberate and precise design of the processing tool, including:

- *Refined pin and shoulder profiles:* selecting an optimal pin configuration and shoulder geometry ensures uniform frictional heat distribution and consistent material flow throughout the process. According to Liew et al., tailoring the tool geometry can significantly reduce localized defects such as voids and incomplete bonding. Additionally, avoiding overly aggressive tool features minimizes flash formation and surface defects [24];

- *Minimizing tool wear*: the incorporation of wear-resistant materials and surface treatments can prolong the tool's effective lifespan. Constant monitoring of tool wear and prompt replacement or reconditioning help prevent geometrical deviations and maintain the desired stirring action [25].

4.2. Fine-tuning of process parameters

Precision in controlling processing parameters is critical for achieving optimal thermal and mechanical conditions:

- *Control of rotational and traverse speeds:* balancing the rotational speed and traverse speed is essential to generate sufficient heat for plasticization without causing overheating. High rotational speeds, if not adequately matched with traverse rates, may lead to flash formation and a softened weld zone, while low speeds may result in inadequate material mixing. Thus, setting these parameters within an experimentally validated window is important [26];
- *Accurate tool plunge depth*: the tool plunge depth must be precisely maintained to allow for complete penetration and effective stirring across the workpiece thickness. An erratic plunge depth can generate regions of inadequate bonding and residual stresses. Dynamic control systems that adjust the plunge depth in real time are recommended to ensure process consistency [27];
- *Adaptive parameter adjustment*: incorporating in-situ monitoring and real-time feedback systems can further refine process control. Flow sensors, thermal imaging, and force measurements enable immediate parameter adjustments, thereby maintaining optimal processing conditions and mitigating defects as they develop [28].

4.3. Material preparation and selection

The selection and preliminary preparation of the aluminium alloy exert a profound influence on the minimization of defect formation:

- *Assessment of homogeneity:* comprehensive microstructural evaluation prior to processing is essential for identifying inherent defects such as porosity or elemental segregation. In the case of cast alloys, which are particularly susceptible to these imperfections, the application of additional pre-processing treatments or the use of higher-quality material batches can significantly reduce the risk of defect propagation throughout FSP/SFSP [29];
- *Surface conditioning:* the meticulous removal of surface contaminants and oxide layers prior to processing is of paramount importance for minimizing the introduction of exogenous inclusions during FSP. The implementation of standardized cleaning protocols and surface treatments is vital to ensure an uncontaminated starting surface.

4.4. Environmental control and SFSP - specific considerations

The regulation of external processing conditions, particularly in the context of SFSP, constitutes a critical component of defect prevention strategies:

- *Selection and regulation of submerging medium (SFSP):* The thermal properties of the submerging medium - including its temperature, thermal conductivity, and stability - play a direct role in determining the cooling dynamics within the processed zone. Maintaining a controlled and stable submerging environment promotes uniform cooling, thereby minimizing thermal gradients and mitigating the development of residual stresses and microstructural heterogeneities [30];
- *Stabilization of ambient conditions:* the maintenance of consistent ambient temperature and humidity levels serves to limit undesirable fluctuations in process parameters. Environmental conditioning of the processing environment is essential to ensure that external variables do not negatively influence the material's behaviour during FSP/SFSP.

4.5. Integration of post-processing treatments

Even when primary process variables are precisely controlled, supplementary treatments can further enhance the quality and performance of the final product:

- *Heat treatment and stress - relief procedures:* the application of post-processing annealing or stress-relief treatments is effective in alleviating residual stresses generated during FSP/SFSP. These procedures are particularly beneficial in achieving microstructural uniformity and restoring the mechanical integrity of the processed material [31];
- *Surface finishing:* mechanical or chemical surface finishing methods are employed to remove any minor surface defects such as flash or superficial tool marks. This finishing step not only improves the appearance but also enhances the overall structural reliability of the material.

5. CONCLUSIONS

This study identified the multifaceted nature of defects arising during FSP and SFSP of aluminium alloys. The findings can be summarized as follows:

Diverse defect manifestations: FSP and SFSP techniques can induce a range of defects, both at the surface (e.g., flash, tool marks, surface cracks) and internally (e.g., voids, porosity, inclusions, unwelded zones, and non-ideal texture development). These defects can compromise the structural integrity and mechanical performance of the processed alloys.

Material - specific considerations: the propensity for certain defects is highly influenced by the initial condition of the material:

- rolled alloys: the inherent texture of rolled alloys is altered during processing due to plastic deformation and grain boundary refinement, which may lead to improved strength and ductility when optimized. However, improper management of process parameters can result in residual stresses and localized stress concentrations, jeopardizing long-term structural integrity and performance;
- cast alloys: cast alloys inherently possess challenges such as porosity, segregation, and microstructural inhomogeneity resulting from the casting process. These issues exacerbate defect formation during FSP/SFSP and result in reduced mechanical strength and complications in subsequent finishing operations.

Influence of process parameters and environmental conditions: the quality of FSP/SFSP outcomes is strongly contingent upon optimizing process parameters, including tool design (pin profile and shoulder geometry), tool rotational speed, traverse speed, and plunge depth. Additionally, environmental factors - such as ambient temperature, humidity, and, in SFSP applications, the characteristics of the submerging medium - play a pivotal role in modulating heat dissipation and cooling rates. These combined influences govern the formation of thermal gradients and the eventual development of residual stresses.

Preventive and optimization strategies: a holistic approach to defect prevention is paramount. Optimal tool design and precise control of processing parameters ensure uniform material flow and controlled heat input, thereby minimizing defect occurrence. Furthermore, the implementation of post-processing treatments, such as annealing or stress-relief procedures, is essential to stabilize the modified microstructure and alleviate residual stresses. The integration of real-time monitoring and adaptive control systems further enhances the ability to maintain optimal processing conditions, thereby significantly reducing defect propagation.

Integration of multidisciplinary approaches: achieving a high-quality, defect-free processing outcome requires a comprehensive strategy that integrates material pre-characterization, stringent process control, environmental stabilization, and subsequent post-processing treatments. Such a multidisciplinary approach ensures a homogeneous microstructure with enhanced mechanical properties, ultimately contributing to the durability and performance of high-performance aluminium components.

The interplay of material properties, process parameters, and environmental conditions defines the occurrence and severity of defects in FSP/SFSP processed aluminium alloys. An integrated optimization strategy is indispensable for advancing these nonconventional manufacturing techniques, thereby enabling the production of superior aluminium components designed for high-performance applications.

6. ACKNOWLEDGEMENTS

The paper was developed within the project PN 23 37 The paper has been developed within the project PN 23 37 01 02 „Research on the modification of metallic materials properties using the innovative and environmentally friendly method of friction stir processing in liquid medium" (financed by the Ministry of Education and Research), NUCLEU Research and Development Program of ISIM Timisoara, contract 16N/2023, PN ISIM 2023-2026.

Also, new and high-performance equipment purchased within the INFRATECH project „Infrastructure for excellence research in welding" (Code SMIS 2014+126084, financed by the Ministry of Research, Innovation and Digitization, as the Intermediate Body for Competitiveness Operational Program 2014-2020, contract 360/390036/ 27.09.2021) have been used to carry out the experimental research.

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