A Literature Review on Ultrasonic Metal Welding for Dissimilar Materials

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***Abstract*—Ultrasonic Metal Welding (USMW) has emerged as a highly efficient solid-state joining technique for bonding similar and dissimilar lightweight metallic materials. The process is widely adopted in automotive, aerospace, and battery manufacturing sectors due to its low heat input, clean joint formation, and suitability for thin foils. This report reviews recent developments in USMW, focusing on interfacial bonding mechanisms, modelling approaches, surface engineering, quality monitoring, and industrial applications. A hybrid literature review approach is adopted, combining both thematic evaluation and key contributions of individual studies. The review highlights the influence of process parameters, surface conditions, sonotrode design, and real-time monitoring on weld quality. Furthermore, current challenges, research gaps, and future prospects for advanced industrial implementation are discussed.**

***Index Terms*—USM welding, Ultrasonic Metal Welding, solid-state welding, process parameters, dissimilar joining.**

I. INTRODUCTION

Ultrasonic Metal Welding (USMW) is a solid-state joining process that utilizes high-frequency vibrations under moderate pressure to produce metallurgical bonds between metal surfaces. Unlike fusion welding, USMW does not melt the parent material, making it highly suitable for joining dissimilar metals that form brittle intermetallic compounds at high temperatures. With the increasing demand for lightweight materials and the rapid growth of electric vehicle (EV) battery technology, USMW has gained significant industrial relevance.

The technique is predominantly used for welding aluminum, copper, nickel, and titanium alloys in the form of foils, sheets, and terminals. Its advantages include low thermal distortion, short cycle time, and excellent electrical conductivity of joints. Recent research has focused on improving process stability, understanding interface microstructure, developing FEM-based predictive models, and implementing intelligent monitoring systems for quality assurance in mass production.

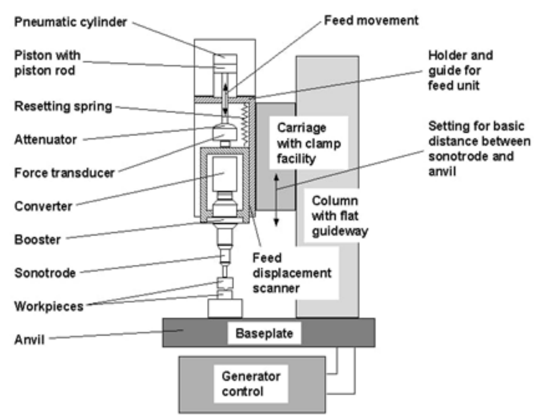

Fig. 1. USM Welding

II. NEED FOR STUDY

The growing shift toward lightweight and energy-efficient systems has intensified the need for reliable dissimilar metal joining. Traditional fusion welding techniques often lead to excessive heat-affected zones, interfacial cracking, and weak joints, particularly when welding Al–Cu, Al–Ti, or Al–Steel combinations. USMW overcomes several limitations;

however, its process behavior is complex due to dynamic plastic deformation, frictional heating, and high-frequency vibration effects.

A systematic literature review is required to:

- Understand interfacial bonding mechanisms in USMW
- Compare advancements in modelling, monitoring, and tool design
- Identify challenges limiting large-scale industrial adoption
- This study provides an integrated perspective to guide academic research and industrial process optimization.

III. LITERATURE REVIEW

1. Thematic Review

a) Interface Microstructure and Bonding Mechanisms

Research indicates that interfacial bonding in USMW is driven by severe plastic deformation, oxide layer disruption, and limited interdiffusion. Formation of a mechanically mixed layer (MML) enhances metallurgical bonding, while excessive energy leads to brittle intermetallic compound (IMC) formation, reducing joint ductility and strength.

b) Modelling and Simulation Advances

FEM-based thermo-mechanical models have been developed to simulate frictional heating, stress evolution, and plastic deformation behaviour. These digital models assist in optimizing process parameters, sonotrode design, and predicting weld quality with reduced experimental trials.

c) Monitoring and Quality Evaluation

Recent studies focus on integrating acoustic emission, real-time electrical resistance measurement, and sonotrode vibration signal analysis for in-line process monitoring. Machine-learning-based models are being used to classify weld quality and enable closed-loop control.

d) Surface Engineering and Preparation

Surface oxidation and contamination significantly affect USMW. Pretreatments such as mechanical abrasion, chemical cleaning, and surface texturing improve bonding and electrical conductivity by enhancing oxide layer disruption during welding.

e) Applications in Industry

USMW is widely used for EV battery tab-to-busbar joining, electronic connectors, aerospace structural laminates, and lightweight assemblies due to its clean welds, low heat impact, and high joint integrity.

2. Key Contributions from Major Studies

- Li et al. (2023) optimized USMW for Al–Cu joints and achieved strong metallurgical bonding with low resistance and thin IMC layers for battery applications.
- Zhou et al. (2021) reported that MML formation enhances bonding in Al–Ti welding, while energy excess leads to brittle IMCs.
- Ni et al. (2023) developed FEM for USW showing strong correlation between frictional heating, plastic strain, and metallurgical adhesion.
- Feng et al. (2024) highlighted machine learning-based monitoring systems as the future of automated USMW quality control.
- Pöthig et al. (2023) found that surface oxide removal and roughening significantly improve joint strength and electrical efficiency.
- Zhang et al. (2022) reviewed Al–Steel welding challenges and recommended hybrid USW–laser techniques to limit IMC growth.
- Huang et al. (2023) demonstrated that proper sonotrode resonance and tool tuning improve energy transmission and weld uniformity.
- Thi et al. (2024) presented 3D FEM mapping of temperature and deformation fields to guide process parameter optimization.
- Li et al. (2025) proposed integrating simulation, sensing, and AI for smart manufacturing of dissimilar USMW.
- Kumar et al. (2024) concluded that USMW is superior to laser welding for thin battery foils due to minimal thermal distortion and higher electrical conductivity.

IV. PROPOSED METHODOLOGY

The proposed methodology for further study includes:

Selection of dissimilar metal samples (e.g., Al–Cu or Al–Ti)

Pre-cleaning and surface preparation to remove oxide layers

Experimental USMW trials under varying amplitude, pressure, and welding time.
Characterization of joints using tensile testing, SEM/EDS, and electrical resistance
Data analysis to correlate parameters with weld performance
Development of FEM-based model for predictive behavior
Implementation of a basic signal-based monitoring method

V. DISCUSSION

The reviewed literature establishes that USMW is a highly reliable joining process, particularly for dissimilar lightweight metals in electrification and aerospace sectors. However, the process window is sensitive, requiring careful control of energy input to prevent IMC formation. Integration of multi-sensor monitoring and AI-based classification improves process repeatability. Simulation-based models are highly beneficial but require experimental validation. Surface engineering remains a key factor in improving bonding quality.

VI. CONCLUSION

USMW provides a high-quality, low-heat, and efficient joining technique for dissimilar metals, making it a preferred process in modern manufacturing. The literature highlights substantial advancements in understanding bonding mechanisms, simulation modelling, tool design, and monitoring techniques. However, standardized control systems, multi-scale modelling, and improved sonotrode durability are still needed for scalable industrial deployment.

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