# The Evolution, Technology, and Efficiency of Ultrasonic Welding in Minimizing Material Dislocations

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# CHAPTER 1

# HISTORY OF ULTRASONIC WELDING

Ultrasonic welding is based on the discovery of piezoelectricity by Pierre Curie and his brother Jacques back in 1881. The studies they provided were the necessary basis to develop ultrasonic energy into useful applications such as welding by converting ultrasonic energy into mechanical vibrations. Other work on crystallography by Curie supported the discovery, and his doctoral research proved the existence of piezoelectricity, which is crucial to ultrasonic technology today [1].

***Figure 1:*** *Pierre Curie*

In 1938, the very first patent linked with ultrasonic welding was given in Germany. Resistance Spot Welding: Ultrasound was initially introduced to modify the grain size in resistance spot welding to make it compatible for joining thin wires and foils. This concept, however, was technologically limited due to power constraints in early ultrasonic welding systems [2].

Dr. George Ludwig, a researcher at Pennsylvania University, conducted studies on ultrasound for medical applications in the 1940s. Although his work primarily focused on the detection of gallstones, it laid the principles similar to those later applied in ultrasonic welding and non-destructive material testing [1].

***Figure 2:*** *Dr. George Ludwig*

Ultrasonic welding for metal was first introduced in the early 1950s, primarily for wire bonding, tube sealing, and joining thin metal foils. Unlike traditional fusion welding methods, ultrasonic welding could bond metals without melting, using high-frequency vibrations. The initial applications were focused on non-ferrous soft metals like copper, aluminum, brass, gold, and silver. The technique gradually expanded to include other materials such as steel, titanium, nickel, and even dissimilar combinations like aluminum-to-steel, metal-to-ceramic, and metal-to-glass [3].

Last but certainly not least, ultrasonic welding technology also started to gain popularity for industrial use in the 1960s. The first major step came when a lab manager at Branson Instruments, Robert Soloff, suspended his plastic strips in time along with sealing them accidentally by welding and discovered that different materials could be bonded using ultrasonic waves. This discovery paved the way for ultrasonic welding to be used in treating a variety of applications, and by 1969, companies such as Sonics & Materials were manufacturing products using this technology, including a plastic car [1].

***Figure 3:*** *Robert Solof with ultrasonic welding press 1960s*

Soon, ultrasonic welding became an attractive option as defects that were typical in fusion welding, e.g., the generation of very rigid intermetallic compounds and additional distortion in welded parts, could be avoided. This made it the preferred option for many types of businesses, notably electronics, automotive parts, and medical devices, due to its high-speed production and exceptional weld quality. Welding of thicker metal gauges and a larger variety of material combinations has lately been accomplished [4].

## CHAPTER 2

## TECHNOLOGY OVERVIEW

### 2.1 Working Principle

The principle of ultrasonic welding is based on the conversion of electrical energy to high-frequency mechanical vibrations through a piezoelectric transducer. The resultant vibrations generate frictional heat at the interface of the materials, allowing them to bond under pressure. The characteristics of the process are:

- **Vibration Frequencies**: Typically ranging from **20-27 kHz**, but in some cases it can vary between 9.5-75 kHz. Higher frequencies allow for more precise control and stronger welds.
- **Amplitude**: Vibration amplitude can range usually from **20 to 60 µm** but it can be different for specific welding process, influencing the amount of frictional heat generated.
- **Pressure and Time**: Applying controlled pressure during the vibration phase is crucial. Welding times can vary from **0.1 to 5 seconds**, depending on material properties and application requirements.

### 2.2 Equipment and Components

Ultrasonic welding equipment consists of a machine press, generator, converter or transducer, booster, sonotrode or horn, and component support tooling. (Ultrasonic welding components)

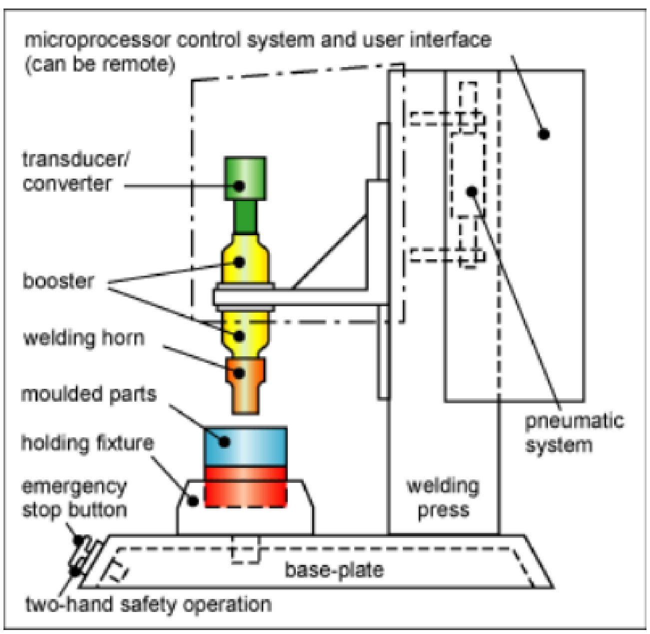


***Figure 4:*** *Schematic of ultrasonic welding machine*

### Generator

The generator takes electrical power from the mains and adjusts it to the right frequency and voltage for the transducer, which then converts it into mechanical vibrations needed for welding. A microprocessor oversees the entire welding cycle and gives crucial feedback to the user through the interface. This interface also enables the operator to conveniently enter essential parameters such as welding time and pressure, ensuring accurate control over the welding process and achieving the best results.

### Machine Press

The machine stand is designed to support the welding system which applies the necessary welding force through a pneumatic cylinder and a base plate that secures the tooling jig. It features a pressure gauge and regulator for adjusting the welding force, though the settings on the gauge may vary between different machines. For accurate calibration, the welding force should be measured with a load cell.

Furthermore, the machine comes with a flow control valve to adjust the approach speed of the welding head. Some of the newer models use an electromagnetic force system, which offers improved control, especially for smaller or more delicate components.

### Welding Stack

This is the part of the machine that provides the ultrasonic mechanical vibrations. It is generally a three-part unit consisting of a transducer, booster, and welding horn, mounted on the welding press at the center-point of the booster section. The stack is a tuned resonator, rather like a musical instrument tuning fork. In order to function, the resonant frequency of the tuned welding stack must closely match the frequency of the electrical signal from the generator (to within 30 Hz).

### Transducer

The transducer, which is sometimes referred to as a converter, is in charge of transforming the electrical energy supplied by the generator into mechanical vibrations in order to facilitate the welding process. There are a number of piezo-electric ceramic discs and they are placed between two titanium blocks.

A dielectric disc lies above each of the discs, serving as an electrode. This sinusoidal electrical signal is supplied to the transducer through the electrodes making the discs to expand and relax, thereby creating a peak-to-peak axial motion of 15 to 20 μm.

Transducers are delicate devices and should be handled with care. Once the elements are broken, the transducer will not function.

**Booster**

The booster section of the welding stack has two main functions: it amplifies the mechanical vibrations generated at the transducer's tip and transfers these vibrations to the welding horn. Additionally, it serves as a mounting point for the stack on the welding press. The booster expands and contracts as the transducer applies the ultrasonic energy.

The booster, like other elements in the welding stack, is a tuned device therefore it must resonate at a specific frequency in order to transfer the ultrasonic energy from the transducer to the welding horn. In order to function successfully, the booster must be either one half of a wavelength of ultrasound in the material from which it is manufactured, or multiples of this length. Normally, it is one half wave length.


***Figure 5:*** *Ultrasonic welding boosters*

**Welding Horn (Sonotrode)**

The welding horn transmits energy to the part being welded. Its design is essential for effective welding and should be produced by specialized manufacturers. Usually crafted from aluminum or titanium, the horn also offers mechanical advantage. Aluminum is preferred for low-volume applications because of wear issues, while hardened tips can help minimize wear.

The horn needs to be tuned to a specific length, which is usually half a wavelength or its multiples, to achieve the right amplitude for welding, generally ranging from 30 to 120μm. Axial expansion can create stress that leads to cracking, particularly in high-amplitude situations, so the horn is often slotted to direct vibrations effectively. Additionally, the tip is tailored to the component to ensure optimal energy transfer.

There are several types of horns used in ultrasonic welding (Types of horns in ultrasonic welding), including:

1. **Tapered horns:** These horns are used for general-purpose welding and are the most common type of horn used in ultrasonic welding. They have a gradually decreasing diameter from the base to the tip, which helps to focus the ultrasonic energy.
2. **Stepped horns:** These horns have multiple diameters along their length, which can help to distribute the ultrasonic energy more evenly across the part being welded. They are often used for parts with irregular shapes or for welding multiple parts at once.
3. **Flat-face horns:** These horns have a flat tip and are used for welding parts with flat surfaces. They distribute the ultrasonic energy more evenly across the surface of the part being welded, which can help to prevent damage or deformation.
4. **Booster horns:** These horns are used to increase the amplitude of the ultrasonic vibrations. They are placed between the ultrasonic generator and the sonotrode, and they can help to amplify the energy of the vibrations, allowing for more efficient and effective welding.
5. **Cylindrical horns:** These horns have a cylindrical shape and are often used for welding pipes or other cylindrical parts. They can help to evenly distribute the ultrasonic energy around the circumference of the part being welded.

The choice of horn type depends on the specific application and the geometry of the parts being welded. Each type of horn has its advantages and disadvantages, and selecting the appropriate horn can help to ensure a successful and efficient welding process.

***Figure 6:*** *Ultrasonic Welding Horns (Sonotrodes)*

**Support tooling**

The base of the machine press provides support for the tooling that holds the components in place during the welding process. This support tooling is specifically designed to keep the lower component stable while the ultrasound is being applied. It is typically machined to closely fit the contours of the component's surface.

## 2.3 Comparative Analysis of Ultrasonic Welding Processes

Here's a consolidated comparison of the ultrasonic welding processes based on the details extracted from several documents:

| Parameter | Frequency | Welding Tip Material | Tip Diameter | Amplitude | Pressure | Welding Time | Power | Materials |
|---|---|---|---|---|---|---|---|---|
| **Study** [1] | Not specified | Not specified | Not specified | 50 µm | 0.345 MPa for trigger & welding pressure | 0.3 s | Not specified | Copper and austenitic stainless steel |
| **Study** [2] | 20 kHz | Not specified | 5-7 mm | Not specified | 2350 N clamping force | Not specified | 4 kW maximum output | Pure copper sheets |
| **Study** [3] | 20 kHz | Not specified | 6-8 mm | 58 µm | 30-60 psi (varied clamping pressures) | Approx. 0.14 - 0.24 s | 2.4 kW | 3003 Aluminum and 304 Stainless Steel |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Study** [4] | 15–75 kHz (most commonly 20 kHz) | Titanium or Aluminum | 6-8 mm | 30-60 µm | 0.345 MPa (40-60 psi) | 0.2-5 s | Up to 2.4 kW | Aluminum Copper, Stainless Steel |
| **Study** [5] | 9.5 kHz and 27 kHz | Hard metal and tungsten | 2-3 mm | Approx. 5 µm (peak-to-zero value) | Static clamping force of 140 N | Approx. 0.5-1 s | Not specified | Aluminum copper, nickel-clad copper, and steel |
| **Study** [6] | 15 kHz | Not specified | 9 mm | 45 µm (peak-to-peak) | 588 N, 882 N & 1176 N | 0.6-1.5 s | 1.2 kW max | Aluminum (A1050P), Copper (C1220P), and Austenitic Stainless Steel (SUS304) |
| **Study** [7] | 20 kHz | Not specified | 14-16 mm | 7–12 µm | 0.6 MPa | 0.1-1.5 s | 8 kW | Aluminum (1060) and Copper (T2) |
| **Study** [8] | 20 kHz | Titanium or Aluminum | Not specified | 25-86.2 µm | 3-5 bar | 0.5-1.5 s | 5 kW | Carbon Fiber/PEEK, Carbon Fiber/Nylon 66, and others |
| **Study** [9] | 15 kHz and 27 kHz | Not specified | 20 mm (in some cases) | 15.5 µm to 25-30 µm | Not specified | 0.3-0.6 s | 50-100 kW | Al, Cu, Steel & Al alloy |
| **Study** [10] | 20 kHz | Aluminum alloy | 20 mm | 40 µm (1st stage) and 56 µm (2nd stage) | Not specified | Not specified | Not specified | AZ31B Mg alloy and CFR PA66 (CF/PA66) |
| **Study** [11] | 15-40 kHz | Not specified | Not specified | Typically ranges between 25 and 86 µm | Ranges from 3-5 bar | 0.5-1.5 s | operate up to 5 kW | Al, Cu, and composites such as CF/PA66, CF/PEEK |
| Study [12] | 20 kHz | Not specified | Not specified | 30–33 µm, 60–75 µm | 0.5-4.5 bar | 0.4-4 s | Not specified | Polypropylene (PP), Acrylonitrile Butadiene Styrene (ABS), Glass Fiber-Reinforced Polymers (GFRP) |

***Table 1:*** *Comparative analysis of ultrasonic welding processes across multiple studies*

This table represents a comparison analysis performed between several studies for the ultrasonic welding process. The most important parameters that were taken into consideration and presented on the comparison analysis are the frequency of vibration, the material used for the welding tip, the tip diameter, amplitude, pressure, power, maximum breaking force, compatibility of the materials, and the time of welding. Ultrasonic welding is one of the welding methods in which high-frequency vibrational energy is used to bond materials together at very high strengths, and its application can be made on automotive, aerospace, and electronic products.

But what is more important to recognize is the fact that all of these parameters have some exceptional values based on welding machines and materials used, in addition to the overall experimental setup. These variations will only reflect the flexibility of the ultrasonic welding process and how important it is to work out the parameters with a view to gaining optimum results on various materials.

1. **Frequency:**

   In most of the studies, the frequency of vibrations falls within the range of 15 kHz to 40 kHz, while the frequency most applied is at 20 kHz. Ultrasonic welding machines generally fall in this category for producing high-frequency vibrational energy that would cause frictional heating at material interfaces. In fact, the exact frequency could be different and is dependent on the machine and sometimes even on the material being welded-especially for those materials which need to be welded with more accuracy or with stronger energy input.

2. **Welding Tip Material:**

   Titanium and aluminum are the most frequently used materials for the welding tip (Sonotrode). The high resistance of wear and durability of titanium provides long life even under extreme applications, while aluminum is lighter and comparatively cheaper. There are some material choices depending on the welding machine and materials joined, but generally, there are some variations among the studies.

3. **Tip Diameter:**

   In these studies, the tip diameters vary from 5.7 mm up to 20 mm, though exceptional values might depend on the particular application and material of welding. With smaller tip diameters, more focused energy transfer is obtained, suitable for applications that require high precision, while larger diameters are needed for welding bigger or thicker materials. In some studies, the tip diameter has not been specified; this is presumably simply because it will depend upon both the machine and the materials being processed.

4. **Amplitude:**

   The amplitude has a great difference between one publication and another, ranging from 5-7 μm (in some cases) up to 86.2 μm, but the amplitude corresponds to the intensity of the ultrasonic vibrations. Higher amplitudes produce more heat, fitting for welding thicker or tougher materials such as metals and composites. Lower amplitudes fit for delicate materials; they ensure that controlled energy input is provided to the weld. Some cases show greatly different amplitudes depending on the material and the energy required.

5. **Pressure:**

   Values for pressure in studies vary from 0.3 MPa to 0.6 MPa and others also use static clamping forces, while this pressure basically played a great role in providing proper contact between materials during the welding process. Strength and quality of weld would be highly affected by this pressure. Special pressure values might be required for different welding machines and setups of welding, which depends upon material type and thickness of sheet, or as highlighted, application of this parameter is very specific.

6. **Welding Time:**

   The welding time is relatively short, ranging from 0.1 to 5 seconds; it relies on both the material and the process. However, there are very few cases of extreme welding time, depending upon material thickness, weld strength needed, and the type of the ultrasonic welding machine that is being used. For example, higher material thickness or more complex welds may require slightly longer time for the proper bonding.

7. **Power:**

   We can see a big difference in power output reported in ultrasonic welding, from up to 100 kW in some studies, while others do not specify the power. Power determines the amount of generated heat at the weld interface, and more demanding materials being welded clearly require higher power, such as metals being welded together. Values of power may be very different depending on the capabilities of the machine and the materials that are intended to be used, especially in the welding of composites or metals.

8. **Material Compatibility:**

The materials to be welded involved a range of materials such as aluminum, copper, stainless steel, polypropylene (P), acrylonitrile butadiene styrene (ABS), and composites such as carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP). It is quite feasible to modify the ultrasonic welding machines to accommodate a wide range of properties in different materials. However, most of the extraordinary material combinations need adjustments in welding parameters, such as special designs of the tips or energy input, to ensure appropriate bonding.

**Similarities:**

- **Frequency:** Most of the studies applied the frequency value at 20 kHz, which is considered a standard in ultrasonic welding. This frequency is optimal for establishing high-frequency vibrations necessary to effectively weld the greater part of materials.
- **Material Compatibility:** All the reviewed studies thus focused on metallic materials such as aluminum, copper, and stainless steel, besides polymers and composites like PP, ABS, CFRP, and GFRP. This can be considered to prove the wide applicability of ultrasonic welding to all types of materials.
- **Welding Time:** The welding time was similarly short across the studies, ranging from 0.1 to 5 seconds for most, evidencing their efficiency.

**Differences:**

- **Amplitude:** The amplitude values were quite variable between studies, with one value as low as 5 µm and another as high as 86.2 µm. Generally, higher amplitudes are utilized for the welding of tougher or thicker materials while low amplitude is used for more delicate materials to ensure that precise energy is applied accordingly.
- **Pressure:** Pressure applied on the different materials and applications varied between 0.3 MPa and 0.6 MPa. Other research does not provide the pressure in bars or MPa but indicates the forces which were applied based on static clamping.
- **Power:** The power levels also ranged from as low as 1.2 kW up to as high as 100 kW, while many studies did not specify the power used. This would seemingly indicate that any power requirements are extremely material- and thickness-specific.

From this analysis, it emerges that ultrasonic welding is quite a flexible and efficient process, capable of welding metals, polymers, and composites. The most commonly used frequency is 20 kHz, while materials such as titanium and aluminum are preferred for the welding tip. However, there are exceptional values for each of these parameters, depending on the particular ultrasonic welding machine and the materials across different uses. Parameters such as amplitude, pressure, power, and welding time need to be intricately adjusted based on material properties and the requirements of the weld.

These deep variations underline how important customization is in processes involving ultrasonic welding. Each one of the parameters-from amplitude to pressure to power-can take any value within a wide range, depending on the type of material being welded and the equipment used. Generally speaking, ultrasonic welding can join a wide range of materials very rapidly and reliably, considering that the key parameters are adjusted for each application. It is this flexibility that generally makes ultrasonic welding best fitted to industries where precision, efficiency, and versatility in materials are required.

## 2.4 Key Findings and Observations

### 2.4.1 Process Efficiency

The results of all studies conducted prove that it is feasible to join metals without filler material through the method of ultrasonic welding.

For example, Study [6] shows that ultrasonic welding is a solid-state process without melting and cooling, and therefore it is time- and energy-saving. This process uses high-frequency vibrations and pressure for strong weld delivery at fast speeds. Absence of any kind of filler material makes this process simpler, reduces preparation and application time, and lowers the costs. It bonds metals like aluminum, copper, and stainless steel through frictional heat, reducing material and labor expenses. Thus, ultrasonic welding can form strong bonds in 0.6 s at bonding forces of 588 N, 882 N, and 1176 N. This process can be applied to several industrial applications.

### 2.4.2 Limitations of Ultrasonic Welding for Hard Metals and Dissimilar Materials

Indeed, ultrasonic welding effectively joins soft metals like copper, aluminum and some polymers, since the process uses high-frequency vibrations to first create friction and then bond materials at their interface. But in hard metals like magnesium and titanium, the process becomes more challenging. These materials demand more precise control of the welding parameters since they easily form brittle intermetallic compounds, or bonds are less efficient due to higher hardness and low ductility [13].

Apart from that, joining various materials, like metals with plastics, is another challenge. This situation causes differences in thermal and mechanical properties, including problems in melting points and expansion rates, which make the formation of a reliable joint quite hard. In some other cases, specialized techniques or interlayers have to be used for overcoming such problems, adding much-muddled complexity to the process. Despite these limitations, advancements in ultrasonic welding technology continue to improve its applicability for difficult materials.

### 2.4.3 New Methods of Ultrasonic Welding

1. **Ultrasonic Extruded Weld-Riveting (UEWR)**

   The Ultrasonic Extruded Weld-Riveting (UEWR) [10] process represents a new approach for joining hard metals, such as AZ31B magnesium alloy, with carbon fiber-reinforced PA66 (CFRTP). This innovative method offers several advantages:

   - **High Tensile Shear Strength:** The tensile shear strength realized from the UEWR process is much higher, as high as 56.5 MPa, against the generally obtained 4-13 MPa by conventional methods like hot pressing. This makes it highly effective in applications where robust joints are required.
   - **Optimized Parameters:** The process uses 2800 J of welding energy with an amplitude of 50-70% and 600 N of welding force to give strong bonds with very minimal defects like voids. Precise control of parameters ensures efficient bonding of hard metals, like magnesium to thermoplastics .
   - **Minimized Defects:** By fine-tuning welding and trigger forces, UEWR limits defects to ensure appropriate molten flow of CFRTP into the pre-drilled holes in magnesium. The result is a strong mechanical interlock.

- **Superior Performance:** Compared to laser welding and hot-pressing, for instance, much stronger and reliable joints are obtained from dissimilar materials by UEWR, particularly those having large differences in their mechanical and thermal properties. Therefore, it will be very ideal in industries such as automotive and aerospace industries.

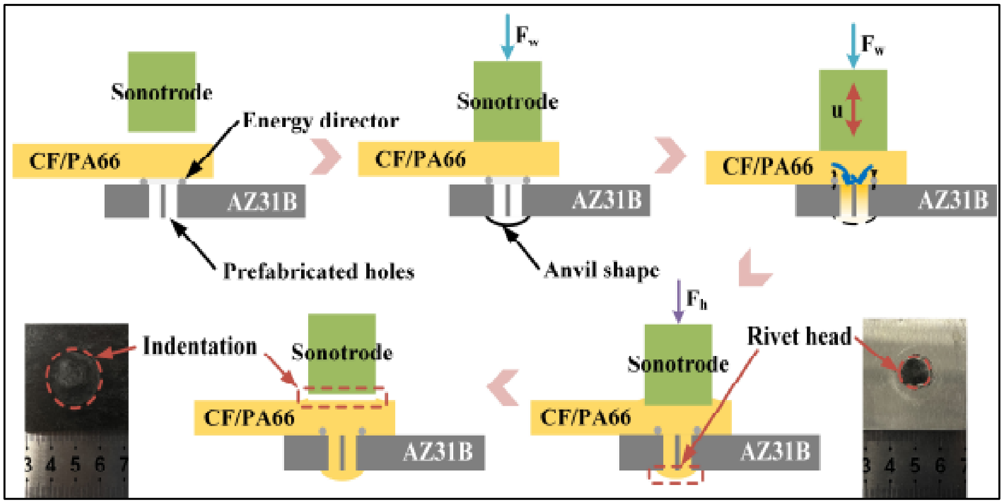


***Figure 7:*** *Schematic diagram of the ultrasonic extruded weld-riveting process. "$F_w$" means the welding force; "$F_h$" means the holding force*

The figure illustrates the Ultrasonic Extruded Weld-Riveting UEWR process in joining CF/PA66 and AZ31B magnesium alloy. The original CF/PA66 sheet is set on top of AZ31B with the prefabricated holes in the metal aligning first. An energy director concentrates ultrasonic energy at the bonding area. Under ultrasonic energy and pressure provided by the sonotrode, CF/PA66 softens, melts, and flows into the prefabricated holes in the metal. Material fills the hole, taking the anvil shape and creating mechanical interlock.

During the continued ultrasonic energy, the formation of CF/PA66 into a rivet head mechanically locks with the AZ31B. A clear indentation of the sonotrode and final rivet head assures strong mechanical bonding between these two dissimilar materials.

## 2. Ultrasonic Butt Welding and Two-Vibration-System Welding

Two techniques for joining dissimilar materials by ultrasonic welding [9] are also represented in this study. One of them includes ultrasonic butt welding, which joins materials by creating friction and heat due to high-power vibrations at the interface without any filler material or excess heat input. In the case of thicker materials, this will be a very good technique because assured strength will be there in the bond without causing damage to the material due to heat.

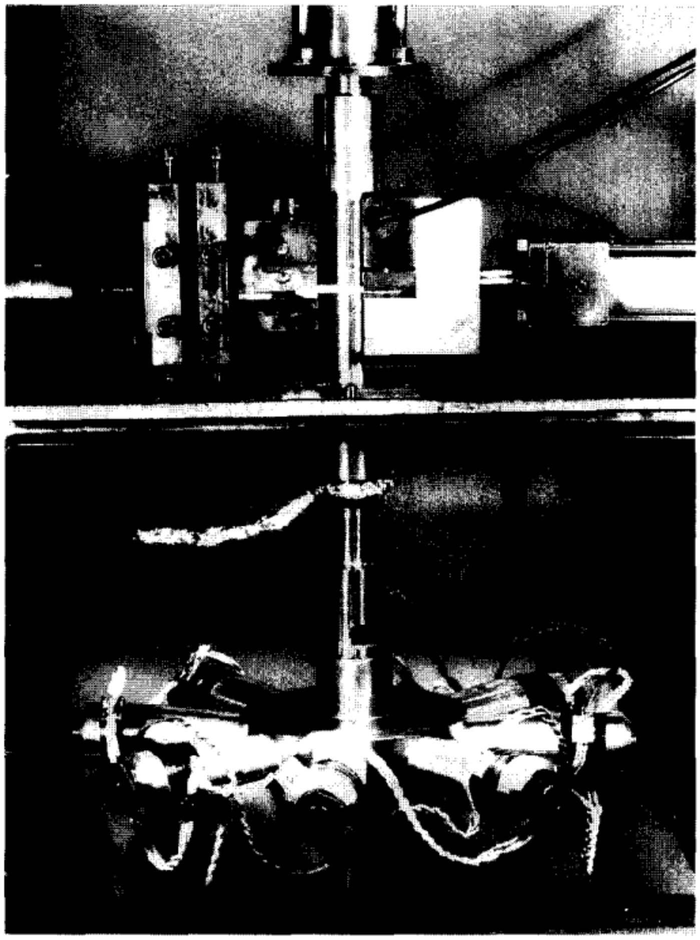

***Figure 8:*** *The ultrasonic butt-welding system uses a 15 kHz vibration source with eight bolt-clamped Langevin-type PZT transducers (60 mm diameter), mounted in the lower part of the equipment*

Another technique described is two-vibration-system welding. During this process, ultrasonic energy applied from the upper and lower sides acts together on the materials. This enhances bonding of larger, thicker specimens by allowing the ultrasonic energy to efficiently create vibrations. Complex vibration tips making elliptical or rectangular patterns are used in smaller or intricate parts to enhance bonding in medium-sized specimens.

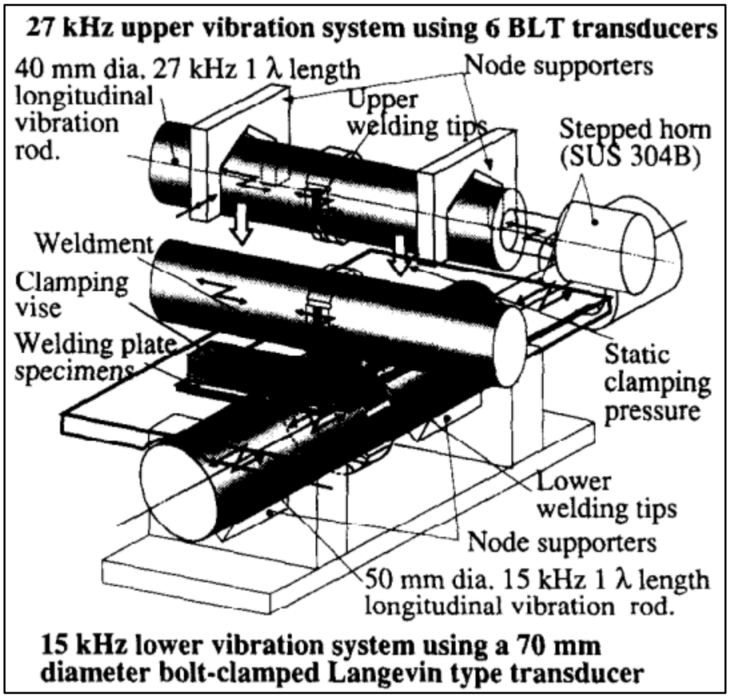


***Figure 9:*** *The ultrasonic lapped spot-welding system uses two longitudinal vibration sources with 27 kHz and 15 kHz systems, arranged at a right angle*

Among the described ultrasonic welding techniques-including ultrasonic butt welding and two-vibration-system welding-joining softer metals like aluminum, copper, and steel to polymers has been generally possible. These bonding processes indeed produce strong heat-efficient bonds that find applications widely in different industries. However, joining harder metals like magnesium and titanium presents additional challenges due to their higher hardness and unique mechanical properties.

Ultrasonic welding of magnesium and titanium seems to be more challenging because these metals, when joined to dissimilar materials like polymers, tend to form intermetallic compounds, which result in brittleness. However, under highly controlled conditions, ultrasonic welding can provide bonds, but the joints may be more fragile than those involving softer metals.

The joining of metals like magnesium and titanium to plastics, due to the thermal and mechanical differences in properties, such as that for the melting points, may result in poor bonding and material degradation. To address these issues, researchers sometimes use interlayers or additives to facilitate the bond between metals and polymers.

While ultrasonic welding is promising, there are a number of limitations in respect to effectiveness in the joining of hard metals to plastics and usually requires additional techniques to help the bond. Research into improving the different methods for the joining of various hard metals to plastics using ultrasonic welding is continuous, trying to meet the challenges and further the reach of the process.

# CHAPTER 3

# DISLOCATION AND CREEP THEORY

## 3.1 The Effect of Ultrasound on Mechanical Properties

During the study of the effects of ultrasound, it has long been observed that the frequency and heat input with which the process takes place significantly influence the properties of the materials. Today, the most important question is the exact understanding of the softening and hardening caused by ultrasonic effects (hereafter referred to as UH), as well as the consequences of plastic deformation that occurs during the process. These factors are largely responsible for the errors presented at the beginning of the work and the final material properties observed after the process. One of the most influential phenomena affecting dislocation density is the degree of deformation, which can increase the dislocation density by 3 to 4 times, as illustrated in Figure 10. The creation of these requires continuous stress, which maintains the process as long as sufficient energy is available for it. [14]

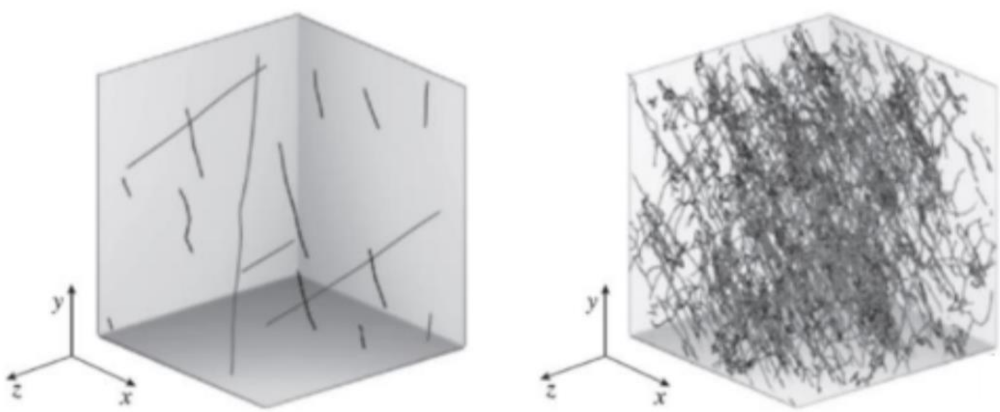


***Figure 10:*** *Dislocation density* [15]

The figure shows two different representations of material structures. On the left, the structure has a rather low level of dislocations indicated by a number of simple, straight lines. On the right, it is highly connected with a large density of dislocations-what can be explained by a complex and knotted network of lines. This is one simple example of how dislocation density might be dramatically increased through deformation or other triggering factors.

Several clear studies have already been conducted on the processes of hardening and softening, from which the following fluctuation can be determined during the process, as shown in Figure 11, which presents the hardening of a test specimen conducted with intermittent ultrasonic vibration experiments:

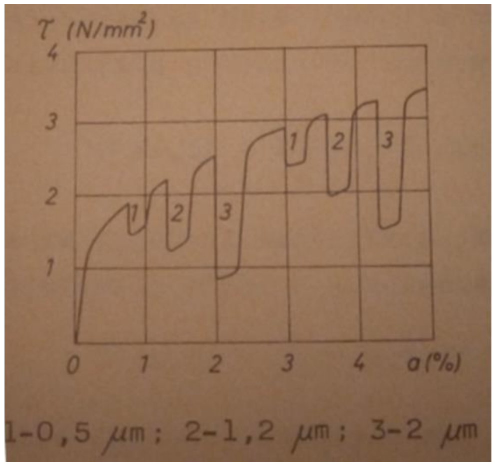


***Figure 11:*** *Curing process diagram* [16]

The graph depicts the hardening process during an experiment with ultrasonic vibrations. The vertical axis (τ) represents stress in N/mm², and the horizontal axis (α) shows strain in percentage. The graph highlights three distinct phases (labeled 1, 2, 3), corresponding to different levels of strain (0.5 µm, 1.2 µm, and 2 µm), with each phase showing a stepwise increase in stress before a decrease, illustrating the hardening behavior under ultrasonic treatment.

### 3.2 The Hardening phenomenon

***Figure 12:*** *Hardening phenomena* [14]

With the support of ultrasonic vibrations and increased temperature, it is much easier for dislocations to move; as a result, materials develop cracks and distortions of the crystal structure. The work by Langenecker in 1966 showed that ultrasound enhances the speed of dislocation movement along the grain boundaries, which impairs formability and reduces tensile strength. The use of bigger loads increases the speed of such a process; thus, at 8.5 MPa, the beginning of dislocation movement was observed after 1 hour, while at 27 MPa, the same process took only 5 minutes. [14]

### 3.3 The Softening Phenomenon

In 1955, two Austrian scientists, F. Blaha and B. Langenecker, studied a single crystal of zinc and found that 800 kHz ultrasonic stress was sufficient to induce elastic deformation in the material, a phenomenon they named ultrasonic softening. The elastic effect caused by ultrasound is highly efficient and can induce elastic deformation in materials that would otherwise be damaged or fail to meet expectations if traditional methods were used. As shown in Figure 13, ultrasound affects the stress in both polycrystalline and monocrystalline structures. In essence, plastic deformation occurs under lower stress in parts treated with ultrasound. [14]

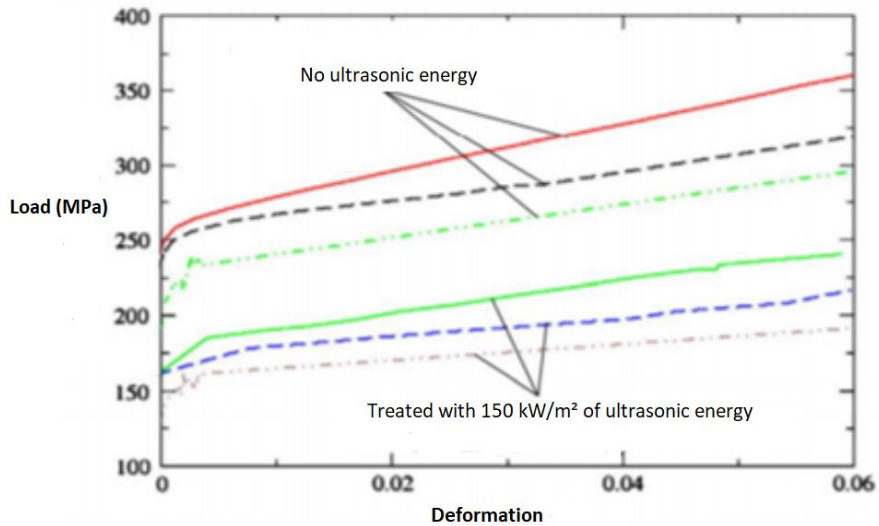


***Figure 13:*** *Effect of ultrasound on tension*

This graph represents the relationship between load in MPa and deformation under various conditions. The red, black and green lines show how the material behaves without ultrasonic energy, while the green, blue and brown lines represent the material response after treatment with 150 kW/m² ultrasonic energy. Under the ultrasonic treatment, the amount of load needed to achieve the same amount of deformation decreases significantly compared to one that is without ultrasonic treatment, which evidences the use of ultrasound to reduce the resistance of the material during its deformation.

Various studies indicate that ultrasonic softening is directly proportional to the intensity or stress amplitude. It permits dislocation movement within the material, loosening the rigid structures that were formed earlier and partially restoring the strength to a value close to the initial one. This process is initiated by heating, which in turn is acting to accelerate further dislocations. Acoustic energy is absorbed mainly by the dislocations, whereas thermal energy redistributes uniformly.

The creep effect in such metals as copper can easily be observed under vibrating stress both in the primary and in the secondary stages, as shown in Figure 14. [14]

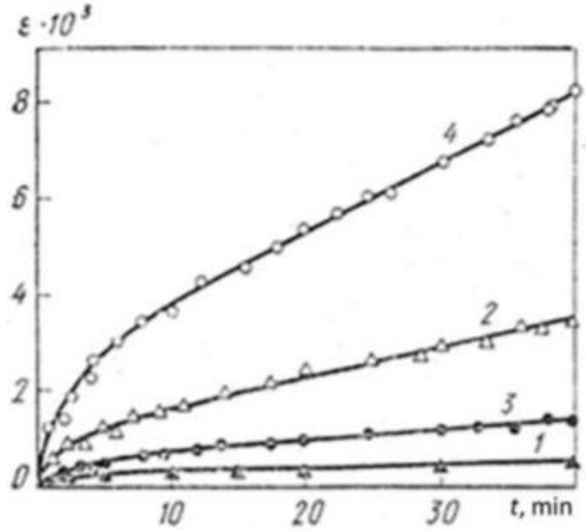


***Figure 14:*** *Copper creep diagrams*

The graph plots the creep curve as a function of time in minutes for various conditions. The vertical axis is the magnitude of strain, ε, multiplied by $10^3$, the horizontal axis is time in minutes. There are four curves on this graph labeled 1 to 4. All four curves show an increased amount of strain as time increases. These curves likely correspond to various conditions of straining or ultrasonic treatment; curve 4 has the highest strain rate, curve 1 is the lowest, and this can be considered as the influence of various treatment parameters on material deformation as a function of time.

### 3.4 Creep phenomenon in ultrasonic welding

Creep, simply put, is a change in length caused by an applied load. This phenomenon also appears in ultrasonic welding, which is not surprising, as the part is subjected to both vibrations from the ultrasound and the applied stress simultaneously. Creep has 3 stages, which are illustrated in Figure 15. The 3 stages shown in the figure are greatly influenced by temperature and load:

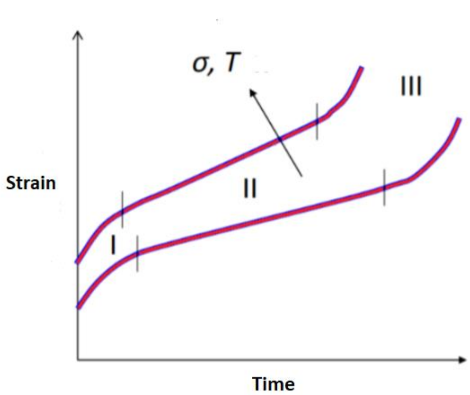


***Figure 15:*** *Creep diagram*

**I - Primary Creep**

**II - Secondary Creep**

**III - Tertiary Creep**

Ultrasonic welding hence appears to be one of the most promising variants for a minimum level of material dislocations due to the combined action of ultrasonic vibrations and heat input. It can be demonstrated from the figures that due to the ultrasonic softening effect, the movement of dislocations within the material can be carried out more easily; hence, plastic deformation at lower applied stresses is enhanced. Special efficiency provides a decrease in dislocations of density that may improve formability and inhibit the development of cracks or other structural defects. By the application of ultrasonic energy, it becomes possible to enhance elastic deformation of materials with the lower dislocation accumulation being harmful; therefore, welding by ultrasound is one of the main techniques in improving the properties of materials during their deformation treatment.

There are some other studies also where it is proven that the ultrasonic welding method is very effective in reducing material dislocation, as discussed below.

### 3.5 Microstructural Changes in Aluminum Foils Under Ultrasonic Welding

The study [17] focuses on the analysis of ultrasonic welding and its impacts on microstructural changes and material dislocation, particularly in aluminum foils.

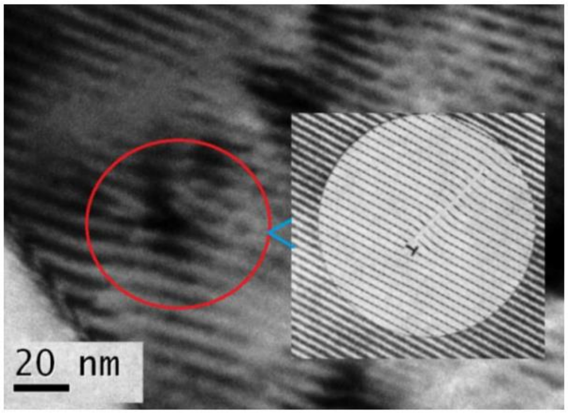


***Figure 16:*** *Dislocation Line*

Here is how ultrasonic welding helps in reducing material dislocation:

**Dislocation Movement:** The high-frequency vibrations during ultrasonic welding cause plastic deformation at the material interface. The oscillations support the dislocation movement within the crystal structure in such a way that the material can rearrange into a stronger bond while minimizing the creation of new dislocations. This movement decreases dislocation density, as noted from the study in Transmission Electron Microscopy (TEM) where the dislocation density in the zone of influence was higher than in the base metal. The result is that the ultrasonic energy will have the effect of triggering a rebuilding process at the crystal structure that will not allow dislocations to accumulate.

**Plastic Deformation and Hardening:** Ultrasonic welding involves the plastic deformation of the materials, meaning that the shape of the materials is changed but not broken. Thus, the material at the welded section will become harder and stronger. Microhardness test results also proved the hardness of the welded section increased compared to the initial material. It means that the ultrasonic welding method contributes to reducing defects but also strengthens the bond.

**Lowering Dislocation Density:** Ultrasonic welding vibrations would help relax the dislocation density (number of defects). Moiré fringes, which represent the dislocations, showed up with TEM analysis to be smaller and more controlled in the welded area compared to the base material, proving that ultrasonic welding manages such defects more effectively.

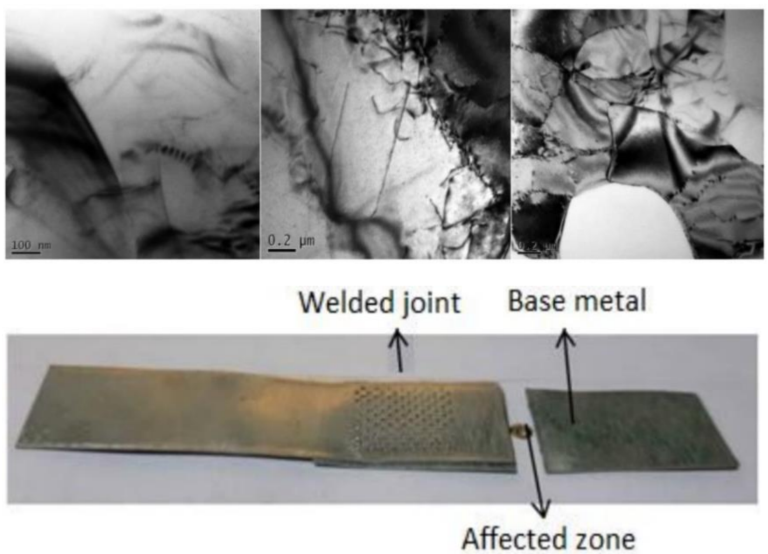


***Figure 17:*** *Welded aluminum foils and TEM images of base metal*

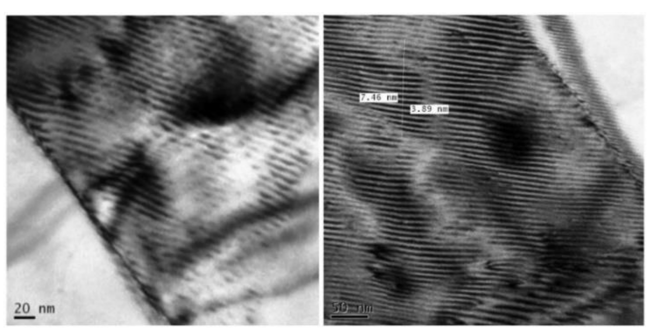


***Figure 18:*** *TEM image of welded zone*

These two figures represent the TEM images that define dislocation density in the base metal and welded zone, respectively. The Moiré fringes that appear in the welded zone have varied within a range of 7.8 nm to 8.2 nm to confirm the controlled dislocation movement due to the ultrasonic process. It is so clear how well the material was controlled in its dislocation within the ultrasonic welding at the microstructural level.

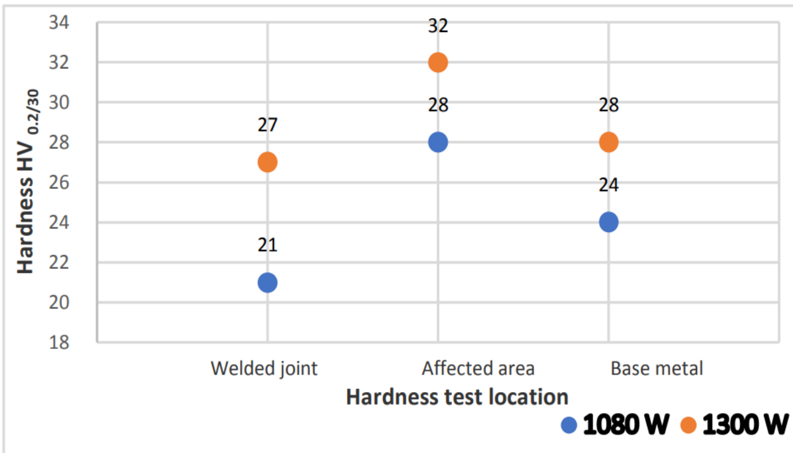


***Figure 19:*** *Microhardness test values depending on the distance of the welded joint*

This graph plots the microhardness values as a function of distance from the weld joint and shows the increase in hardness within both the welded zone and in the affected area. The increase in hardness up to 32 HV0.2/30 shows the rise in hardness indicative of the ultrasonic process, which strengthens the material by reducing dislocation.

### 3.6 Abnormal dislocation structure in ultrasonically welded Cu single crystals

This study [18] focuses on the impact of ultrasonic welding on dislocation substructures in copper single crystals.

**Dislocation Movement:**

The ultrasonic welding encourages high-frequency vibrational motion that enhances dislocation motion and avoids entanglement or pile-up of dislocations during deformation at high strain rates. Dislocation substructures in copper single crystals were examined and showed large equiaxed dislocation cells developed under the action of ultrasonic excitation. These cells helped to minimize the dislocation entanglement, promoted dynamic recovery, and thus reduced the overall dislocation density.

**Dislocation Substructure Analysis:**

The below figure represents the TEM images of dislocation substructures in dynamically recrystallized grain regions and grains affected by shear deformation for two regions. The triangle symbols represent the crystallographic orientation 001, 101, and 111, respectively.

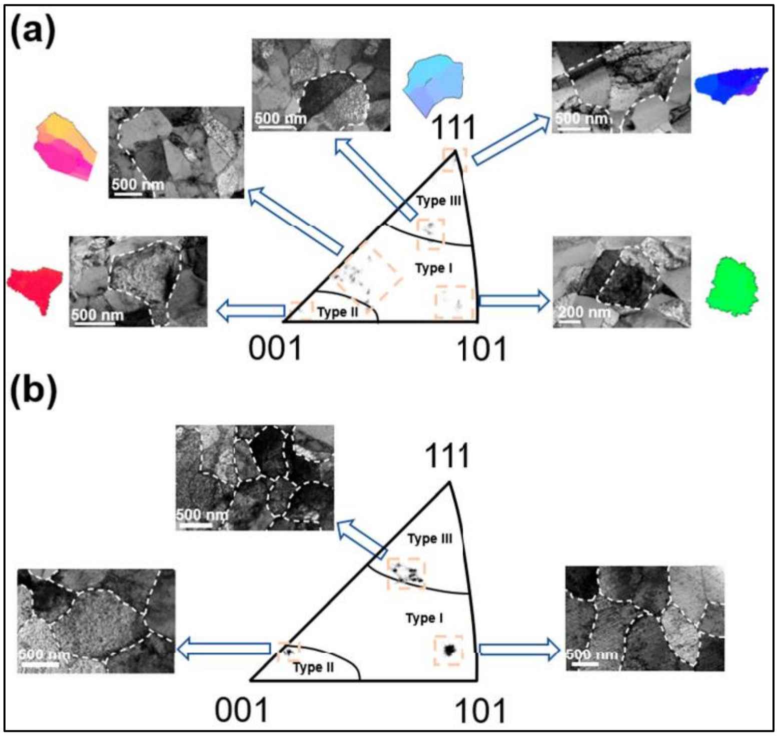


***Figure 14:*** *TEM images and orientations of target grains in (a) DRX grains and (b) shear-deformation regions, divided into Type I-III per Hansen and Winther's research*

- Part (a) identifies regions of DRX grain where dislocations have developed into Type I, II, and III arrangements; TEM images to 500 nm scale are presented to illustrate these for several identified grain orientations.

- Part (b) shows shear-deformation affected regions, whereby the dislocations are also aligned with such grain orientations to develop patterns of deformation.

This figure shows the influence of ultrasonic welding on the dislocation patterns that develop in different grain orientations, enabling us to understand material structures responding at the microscopic level to welding stresses.

**Microhardness and Dislocation Density:**

Ultrasonic welding results in larger dislocation cells (indicating lower dislocation density) and increases the microhardness at the joint interface, making the welded area stronger than the base material.

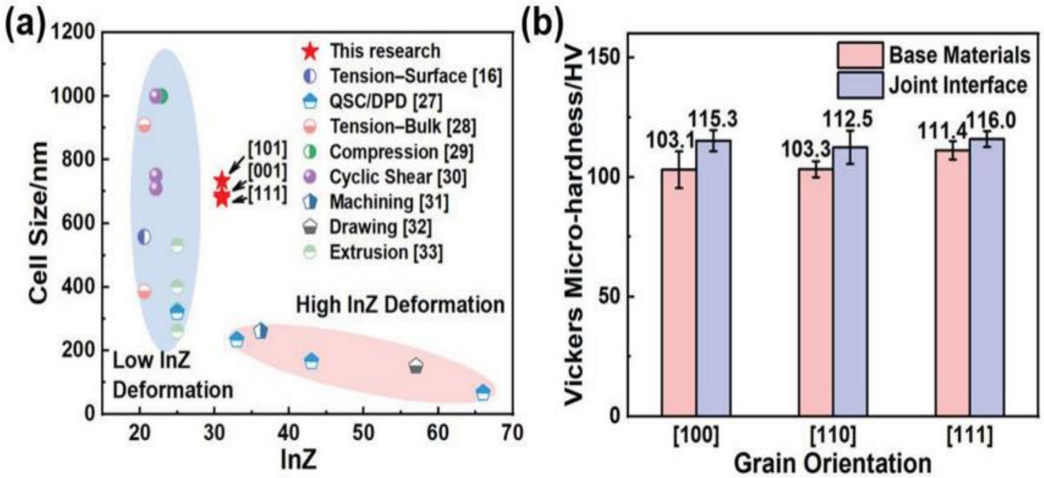


***Figure 15: (a)*** *Shows the relationship between lnZ and dislocation cell sizes in pure copper, using parameters from various studies.* ***(b)*** *Displays Vickers microhardness comparisons between the base materials and the joint interface, showing stronger hardness at the joint.*

This figure provides key information about dislocation density and microhardness.

- Part (a) describes the relation of cell size with lnZ (Deformation Parameter). In this study, the cell sizes generated in the course of ultrasonic welding vary within the range of 600–800 nm for the low lnZ deformation regime, which characterizes better control of dislocation movement, thus resulting in larger cells and a low dislocation density.

- Part (b) shows the Vickers microhardness for base materials (pink) and for the joint interface (blue). The joint interface always exhibits higher hardness; for example, it yields 115.3 HV for the grain orientation along the [100] direction. Material strengthening at the welded joint is due to an improved grain structure with lower dislocation density.

So, Ultrasonic welding offers significant advantages over other conventional welding methods through high-frequency vibrations to create strong bonds without excessive heat, reducing the risk of material distortion and dislocation. It also allows for precise control over bonding, especially with dissimilar materials, ensuring higher joint strength and microhardness. Its ability to minimize thermal damage makes it ideal for industries requiring high precision and efficiency.

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