INVESTIGATION OF MICROSTRUCTURE AND MECHANICAL PROPERTIES OF COLD PRESSURE WELDED COPPER RODS

A FINAL YEAR PROJECT REPORT

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BONAFIDE CERTIFICATE

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TABLE OF CONTENTS

ABSTRACT

Cold pressure welding of copper rods was carried out to study the performance of the joints and to delineate the optimal welding parameters. The critical welding parameters, the normal pressure and the extent of deformation are varied based on the design of experiments. The effect of these critical welding parameters on the joint's efficiency, microstructure, hardness and strength is evaluated. The joints were systematically analysed through the macrostructure, evolved microstructure at various zones, microhardness and their tensile properties. Response surface methodology was applied to arrive at an optimal welding parameter based on the tensile strength output response considering the interaction between the parameters. There were three different zones evolved namely the bonding zone, deformation zone and the base metal with different levels of grain refinement. The extent of deformation showed superior influence compared to the normal pressure over the microstructural zones, their grains, hardness of joints and the tensile strength. Optimized parameters produced high quality joints with suitable microstructure which had strength greater than parent material.

LIST OF FIGURES

LIST OF TABLES

CHAPTER – 1

INTRODUCTION

1.1 COPPER – GENERAL AND OCCURANCES:

Copper has the chemical symbol Cu and the atomic number 29. It is a soft, malleable, and ductile metal with high thermal and electrical conductivity. Copper has been utilized in a variety of applications for thousands of years, including electrical wiring, plumbing, construction, and as a component in coinage and jewellery. Copper is most commonly found in its natural state as an ore, which is a rock with a high concentration of copper minerals. Several steps are involved in the extraction of copper from ore, including crushing and grinding the ore, separating the copper minerals from other materials in the ore, and refining the copper using various techniques.

Copper's propensity to make alloys with other metals, such as brass (copper and zinc) and bronze (copper and tin), is one of its distinguishing characteristics. When compared to pure copper, these alloys frequently have superior mechanical and chemical properties, making them useful in a variety of applications. Copper is a necessary nutrient for all living species, including humans, and is involved in numerous biological processes. Excessive copper exposure, on the other hand, can be poisonous and cause health concerns such as liver damage and neurological abnormalities.

Figure 1.1. Pure Copper

Pure copper metal is relatively soft and easily moulded into various shapes, making it appropriate for a wide range of uses. Because of its great thermal and electrical conductivity, it is an excellent material for electrical wiring and other applications requiring efficient heat and electricity transport. Copper is also antibacterial, which means it may kill or restrict the growth of microbes, making it valuable in hospitals, kitchens, and other places where hygiene is important.

1.2 <u>COPPER – PROPERTIES:</u>

Copper is a chemical element with the symbol Cu and atomic number 29. It is a ductile metal with excellent electrical conductivity, thermal conductivity, and corrosion resistance. Here are some of the properties of copper:

<u>Physical Properties</u>: Copper has a reddish-orange color and a metallic luster. It is a soft metal that can be easily worked into various shapes. Its melting point is 1,085°C, and its boiling point is 2,567°C.

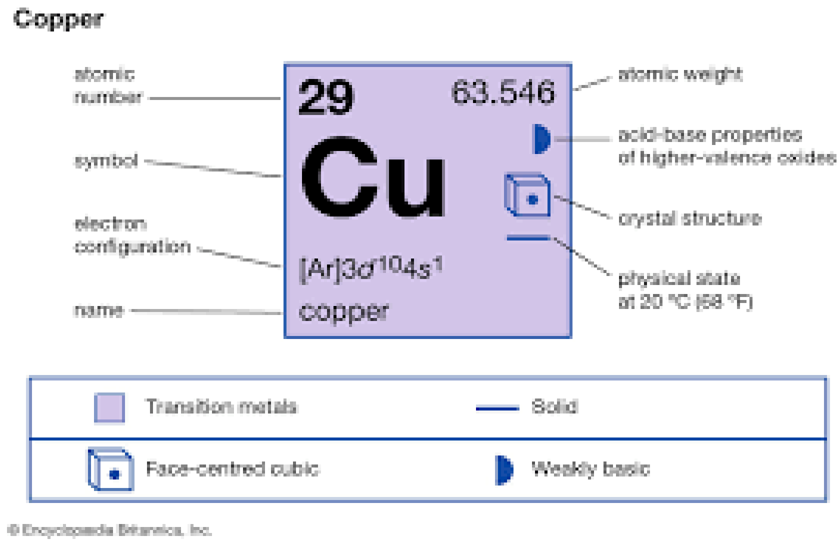


Figure 1.2. Copper Properties

Electrical Conductivity: Copper is an excellent conductor of electricity. It has a high electrical conductivity, second only to silver, which makes it ideal for use in electrical wiring, motors, and transformers.

Thermal Conductivity: Copper is also an excellent conductor of heat. It has a high thermal conductivity, which makes it useful in heat exchangers, solar collectors, and other applications where heat needs to be transferred efficiently.

Corrosion Resistance: Copper is highly resistant to corrosion. It forms a protective oxide layer when exposed to air, which helps to prevent further corrosion.

Malleability and Ductility: Copper is a highly malleable and ductile metal. It can be easily shaped into thin wires or sheets without breaking.

Density: The density of copper is 8.96 g/cm3, which makes it a relatively heavy metal.

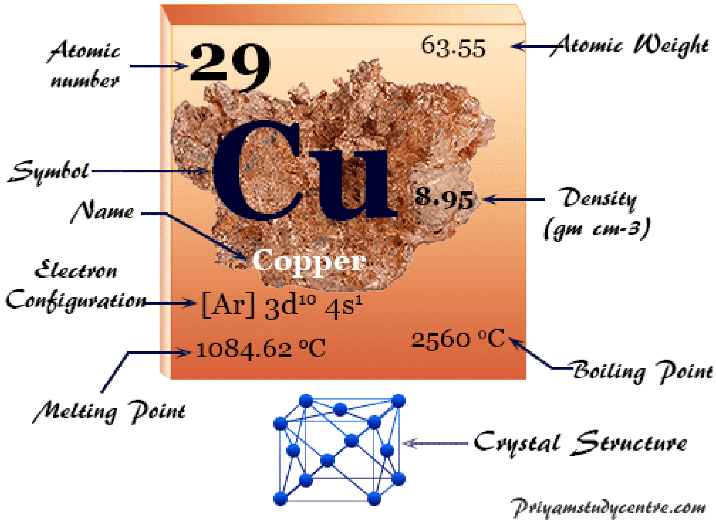


Figure 1.3. Copper characteristics and crystal structure

Copper's crystal structure plays an important role in its properties, such as its high electrical and thermal conductivity. The close packing of atoms in the fcc structure allows electrons to move freely throughout the lattice, contributing to copper's excellent conductivity. The regular arrangement of atoms in the crystal lattice makes it difficult for impurities or defects to disrupt the flow of electrons, which further enhances copper's conductivity

1.3 <u>COPPER – APPLICATIONS:</u>

Copper metal is a soft, ductile, and malleable reddish-brown metal. It has excellent thermal and electrical conductivity, making it a widely used material in electrical wiring and for the production of pipes, tubing, and other products where heat and electricity must be efficiently transferred. Copper is also used extensively in construction and industry, including in roofing, plumbing, and electronics. Copper's unique properties, including its aesthetic appeal, durability, and resistance to corrosion, make it a popular material for roofing, gutters, and decorative elements in architecture and construction. Copper is utilised in a variety of automotive applications, including the radiators, braking systems, and electrical components.

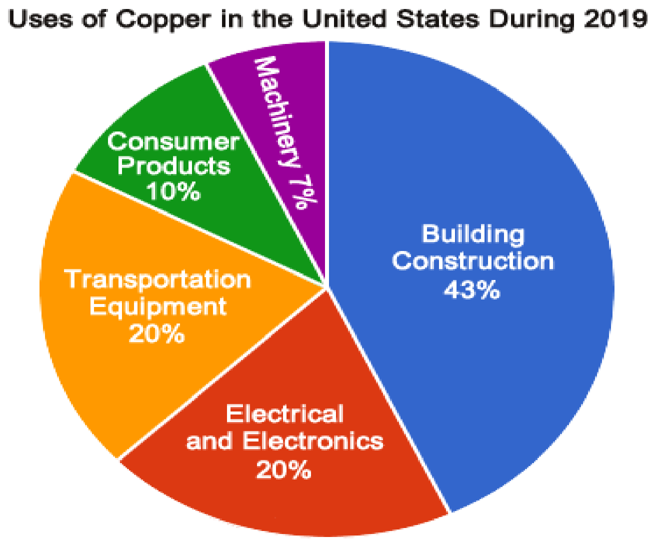


Figure 1.4. Copper applications

Copper is now often utilised for current-carrying components in battery packs, power modules, commercial motors, and other electronic devices. Copper is used mostly in wiring for electricity (60%), roofing & plumbing (20%), and machinery for industry (15%). Copper is primarily used in a pure metal, although when additional hardness is needed, it is included into alloys like brass & bronze (5% of all use). Copper paint was originally used on the hulls of boats for over two centuries to limit the development of plants including shellfish. A tiny portion of the copper supply is utilised in agricultural additives and fungicides. Copper can be machined, although alloys are preferable for improved machinability when producing complicated pieces. Furthermore, copper is a necessary nutrient for human health. Furthermore, copper has become an essential nutrient to human health and can be found in a variety of foods, such as nuts, seeds, seafood, and liver.

Figure 1.5. Various products of copper

1.4 <u>COPPER RODS – APPLICATIONS:</u>

Copper rods are long cylindrical bars made of pure copper or copper alloys. They have a wide range of uses across various industries due to their unique properties, including their excellent electrical conductivity, thermal conductivity, malleability, and corrosion resistance. Here are some common uses of copper rods:

1. <u>Electrical and Electronics:</u> Copper rods are commonly used in electrical and electronic applications, such as grounding systems, lightning protection systems, and transmission lines.
2. <u>Construction:</u> Copper rods are used as reinforcing bars in concrete structures due to their high strength and corrosion resistance.

3. Welding and Brazing: Copper rods are used as filler metal in welding and brazing applications due to their excellent thermal conductivity and corrosion resistance.
4. Manufacturing: Copper rods are used in the manufacturing of various products, including wires, cables, and electrical components.

Figure 1.6. Various application of copper rods.

5. Art and Sculpture: Copper rods are used in the creation of art and sculpture due to their malleability and aesthetic appeal.
6. Jewellery Making: Copper rods are used in the creation of jewellery due to their unique colour and malleability.
7. Plumbing: Copper rods are used in plumbing applications, such as water pipes and fittings, due to their excellent corrosion resistance and durability.
8. Heat Exchangers: Copper rods are used in the manufacturing of heat exchangers due to their excellent thermal conductivity and corrosion resistance.

1.5 NECESSITY FOR JOINING COPPER RODS:

Joining of copper rods is necessary in many applications, especially in electrical and electronic systems, where longer lengths of copper rods are needed to connect different components or to extend an existing conductor. Here are some reasons why joining of copper rods is necessary:

Figure 1.7. Welding of Copper Rods.

1. Length Requirements: In many applications, the required length of copper rods is longer than the available length of a single rod. Therefore, multiple copper rods need to be joined to achieve the desired length.
2. Current Carrying Capacity: Copper rods have a specific current carrying capacity based on their cross-sectional area. In applications where higher currents need to be carried, multiple copper rods may need to be joined in parallel to increase the current carrying capacity.

3. <u>Resistance:</u> The resistance of a copper rod increases with its length. Therefore, to minimize resistance in a circuit, multiple copper rods may need to be joined to achieve the desired length.
4. <u>Connection Points:</u> Copper rods need to be connected to other components or to an electrical circuit. Joining of copper rods allows for the creation of secure and reliable connections.
5. <u>Maintenance and Repair:</u> Joining of copper rods allows for easy maintenance and repair of electrical and electronic systems, as individual rods can be replaced or repaired without affecting the entire system.

1.6 COPPER RODS – JOINING METHODS:

There are several joining methods for copper rods, some of which include:

1. <u>Soldering:</u> This involves heating the copper rod and applying a low melting point alloy, called solder, to the joint. The solder then cools and hardens to create a strong bond between the two copper rods.
2. <u>Welding:</u> This involves heating the copper rods to a very high temperature and applying pressure to the joint until the metal fuses together. This method is typically used for thicker copper rods.
3. <u>Brazing:</u> This is similar to soldering, but uses a higher melting point alloy called brazing filler metal. The filler metal is melted and flows into the joint, creating a strong bond between the two copper rods.
4. <u>Mechanical connections:</u> This involves using mechanical methods, such as bolts, screws, or clamps, to join the copper rods together. This

method is often used when the copper rods are too thick for soldering or welding.

The joining method chosen is determined by a number of criteria, notably the dimension of the copper rods, the application's specifications, and the availability of tools and experience.

Figure 1.8. Soldering

Figure 1.9. Brazing

1.7 <u>ISSUES IN JOINING COPPER RODS:</u>

There can be several issues in joining copper rods, including:

1. <u>Poor joint strength:</u> If the joint is not properly prepared or the joining process is not carried out correctly, the joint may have poor strength and may fail under load.
2. <u>Corrosion:</u> If the joint is exposed to moisture or other corrosive substances, it may corrode over time, weakening the joint and causing it to fail.

3. Thermal expansion and contraction: Copper rods can expand and contract due to temperature changes. If the joint does not allow for this movement, it may become stressed and fail over time.
4. Dissimilar metals: If the copper rods are joined to dissimilar metals, such as steel, the difference in their thermal expansion coefficients can cause stress and lead to joint failure.
5. Surface contamination: If the copper rods are not properly cleaned before joining, surface contamination can interfere with the joining process and weaken the joint.


Figure 1.10. Corrosion

Figure 1.11. Dissimilar Metals

To avoid these issues, it is important to carefully prepare the joint, select the appropriate joining method, and ensure that the joint is properly protected against corrosion and other forms of damage.

1.8 <u>FUSION WELDING OF COPPER RODS – GENERAL AND ISSUES:</u>

Fusion welding of copper rods involves heating the ends of the copper rods until they melt and then bringing them together to form a joint. There are several methods of fusion welding copper rods, including Gas Tungsten Arc Welding (GTAW or TIG), Gas Metal Arc Welding (GMAW or MIG), Plasma Arc Welding (PAW), and Electron Beam Welding (EBW). Fusion welding can produce strong, high-quality joints between copper rods, but it requires specialized equipment and skilled operators.

Figure 1.12. GTAW

Figure 1.13. PAW

There can be several issues in the fusion welding of copper rods, including:

1. <u>Porosity:</u> This occurs when gas is trapped in the weld, leading to weak spots in the joint.
2. <u>Cracking:</u> This can occur if the copper rods are not properly preheated or if the cooling rate is too rapid, causing the joint to crack.
3. <u>Incomplete fusion:</u> This occurs when the heat input is not sufficient to fully melt the copper rods, resulting in a weak joint.

4. Weld distortion: The heat from the welding process can cause the copper rods to deform, leading to distortion or warping of the joint.
5. Contamination: Copper is highly susceptible to contamination from dirt, oil, or other substances, which can cause defects in the weld and weaken the joint.

To avoid these issues, it is important to carefully prepare the joint, select the appropriate welding method, and ensure that the welding process is carried out by skilled operators with the right equipment and techniques. It is also necessary to take precautions to make sure that the copper rods are fresh and devoid of pollutants that might cause problems with the welding process.

1.9 COPPER RODS WELDING – SOLID STATE VS FUSION:

When it comes to joining copper rods, there are several differences between solid-state welding and fusion welding, which include:

1. Heat input: Fusion welding of copper rods requires high heat input to melt the copper, while solid-state welding of copper rods does not require melting, so it can be carried out at lower temperatures and with less heat input than fusion welding.
2. Filler material: Fusion welding of copper rods typically requires the use of filler material to fill the joint, while solid-state welding of copper rods does not require filler material.
3. Joint strength: Solid-state welding techniques such as friction welding and ultrasonic welding can produce joints that are stronger and more uniform than those produced by fusion welding of copper rods.

4. <u>Deformation:</u> Fusion welding of copper rods can cause significant deformation of the copper, while solid-state welding of copper rods produces minimal deformation.

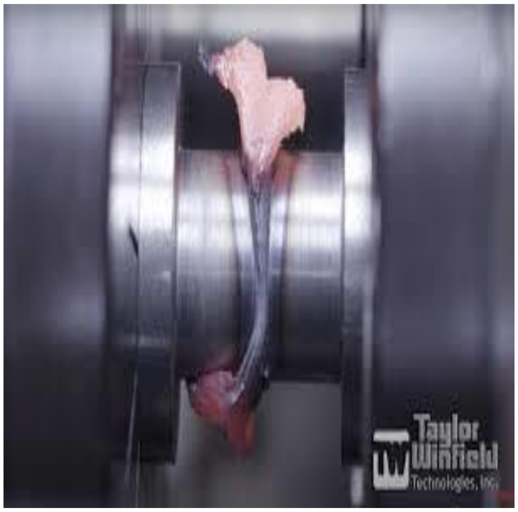


Figure 1.14. Solid-State welding   Figure 1.15. Fusion welding

Generally, solid-state welding of copper rods can offer several advantages over fusion welding, including stronger joints, lower heat input, and minimal deformation. However, it may not be suitable for all applications, and the choice between the two techniques will depend on factors such as the specific requirements of the application, the desired joint strength, and the available equipment and expertise.

1.10 <u>NEED FOR SOLID STATE WELDING OF COPPER RODS:</u>

Solid state welding of copper rods can offer several advantages over fusion welding, including:

1. Stronger joints: Solid state welding techniques, such as friction welding and ultrasonic welding, can produce joints that are stronger and more uniform than those produced by fusion welding.
2. Lower heat input: Solid state welding does not require the high temperatures and heat input of fusion welding, reducing the risk of distortion and other defects.
3. No filler material needed: Solid state welding does not require the use of filler material, simplifying the process and reducing costs.
4. Minimal deformation: Solid state welding produces minimal deformation of the copper rods, which can be important in applications where dimensional accuracy is critical.
5. Environmentally friendly: Solid state welding produces no fumes or harmful gases, making it a more environmentally friendly option than fusion welding.

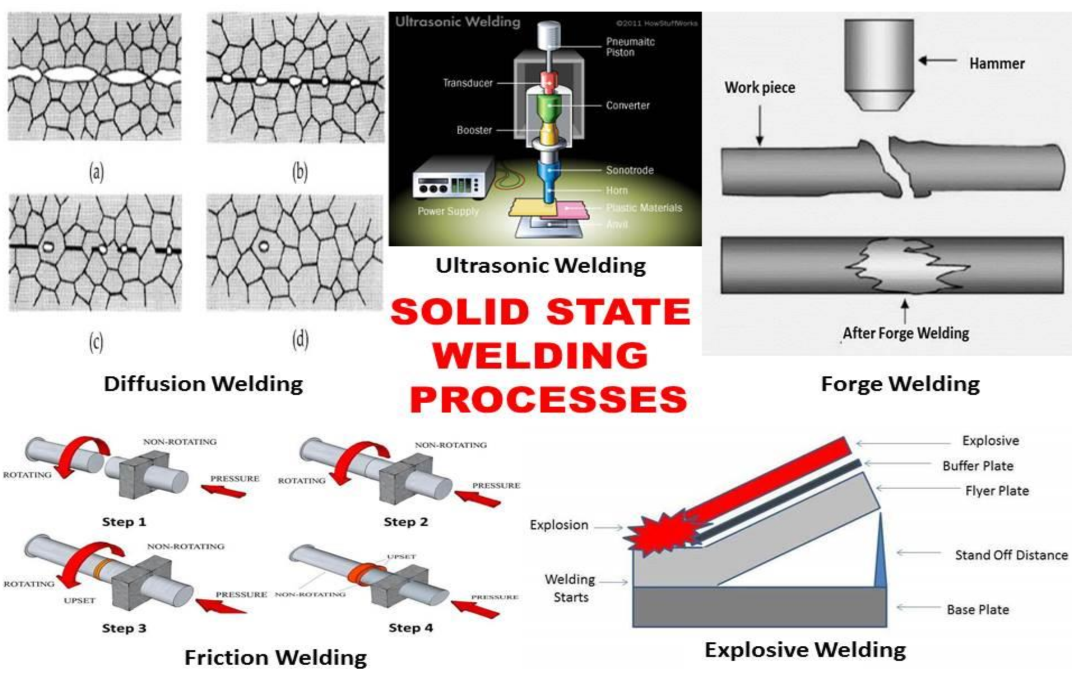


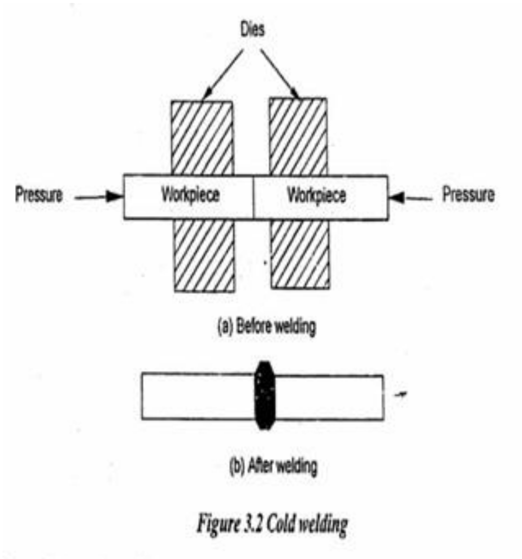
Figure 1.16. Types of solid-state welding

Solid state welding can be particularly useful for joining dissimilar metals, such as copper and aluminum, which can be difficult to weld using fusion welding techniques. However, solid state welding requires specialized equipment and may not be suitable for all applications.

1.11 <u>COLD PRESSURE WELDING – GENERAL:</u>

Cold pressure welding, frequently referred to as or cold welding, is a type of a solid-state process of welding that uses no heat to fuse two metals together. High pressure is applied to the two surfaces of metal to be connected, causing the metals to change shape and bond at the molecular level.

In cold-pressure welding, the two metal surfaces are cleaned and brought into contact with each other. High pressure is then applied to the metal surfaces, typically by using a hydraulic press or similar equipment. The pressure causes the metal to deform and flow, creating a bond between the two surfaces. This method of joining metals without using heat became known for the first time in the 1940s, while cold welding has a considerably longer history. Cold pressure welding is commonly used for joining copper and other non-ferrous metals, as well as for joining wires, rods, and tubes. It can produce strong and reliable joints that are free of voids, porosity, or other defects.



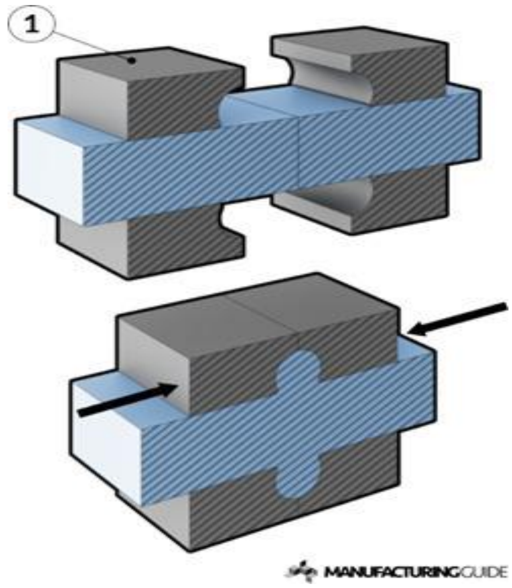


Figure 1.17&1.18. Cold welding process

One advantage of cold-pressure welding is that it does not require any heat, so there is no risk of distortion or metallurgical changes to the metal. It is also a simple and cost-effective process that can be carried out with basic equipment. However, cold-pressure welding does have some limitations. It is not suitable for all materials, and it may require a significant amount of force to achieve a successful weld. Additionally, the quality of the weld can be affected by the cleanliness and surface finish of the metals being joined.

1.12 PRINCIPLE BEHIND COLD WELDING PROCESS:

The principle behind cold pressure welding is that two metal surfaces can be joined together at the molecular level by applying high pressure without the use of heat or filler material. The process involves three main steps:

1. Surface preparation: The surfaces of the two metal parts to be joined are cleaned and brought into contact with each other. The cleanliness and surface finish of the metal surfaces is critical to the success of the process.
2. Application of pressure: A high pressure is applied to the two metal surfaces, typically by using a hydraulic press or similar equipment. The pressure causes the metal to deform and flow, creating a bond between the two surfaces.
3. Finishing: The joint is then typically finished by machining or polishing the welded area to remove any surface irregularities or deformations.

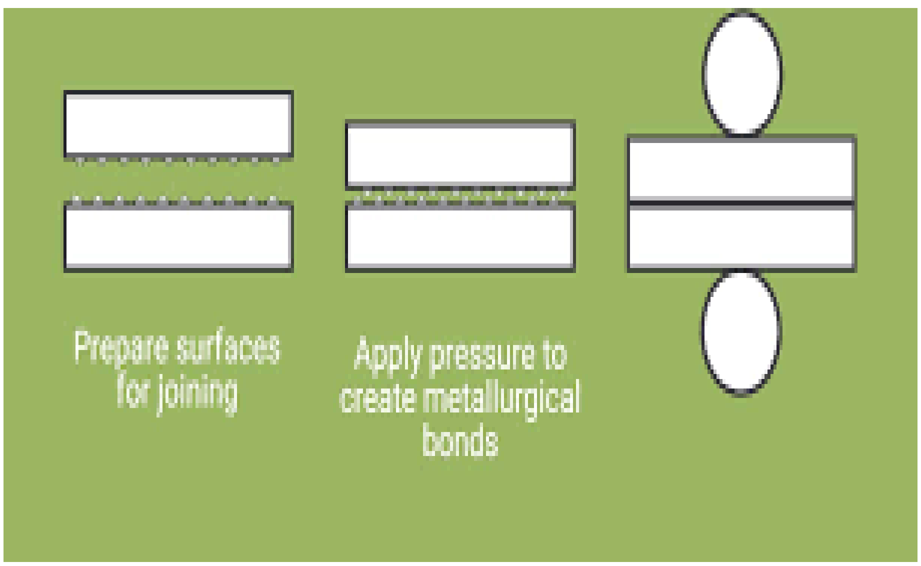


Figure 1.19. Steps involved in Cold pressure welding process

The key to the success of cold-pressure welding is the high pressure applied to the metal surfaces, which causes the metal to deform and bond together at the molecular level. The deformation of the metal surfaces also results in the expulsion of any surface contaminants or oxides, which can interfere with the bonding process. Because the process does not involve heat, the metallurgical properties of the metals remain unchanged, resulting in a strong, reliable, and uniform bond.

1.13 COLD PRESSURE WELDING – BONDING MECHANISM:

The bonding mechanism of cold-pressure welding involves the deformation and diffusion of the metal atoms at the interface of the two metal surfaces being joined. When pressure is applied, the metal surfaces deform and the atoms come into intimate contact with each other. The pressure applied is typically high enough to cause the surface layers of the metals to flow and merge at the atomic level.

As the metal surfaces deform and merge, the atomic lattice structures of the two metals become entangled, creating a strong and uniform bond. This bond is achieved without the use of heat or filler material, resulting in a joint that is free of defects such as porosity, voids, or inclusions.

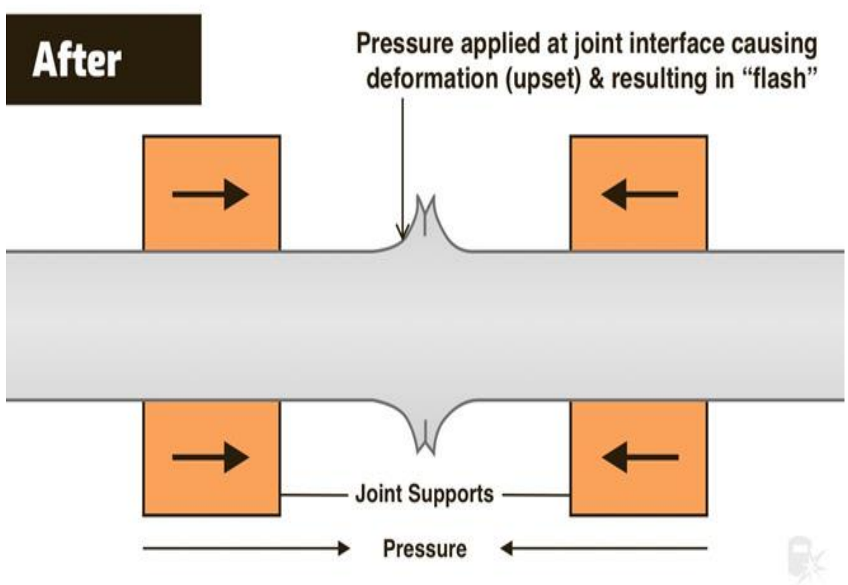


Figure 1.20. Bonding Mechanism of CPW

Cold-pressure welding's bonding method is comparable to the ones of other solid-state welding procedures that include friction welding & ultrasonic welding. Cold pressure welding, on the other hand, is performed at ambient temperature as well as without the utilisation of extra sources of energy like friction or ultrasonic.

Cold pressure welding success is determined by the pristine condition and surface finish of the two metals that are joined, in addition to the quantity of pressure applied. Furthermore, the type of metals being joined, the structure of their crystals, and other factors influencing their physical and mechanical properties can all have an effect on the bonding mechanism.

1.14 CONDITION FOR COLD PRESSURE WELDING:

The success of cold pressure welding depends on several conditions, including:

1. Material selection: Cold pressure welding is most effective for joining metals with similar properties and crystal structures, such as copper, aluminum, and their alloys.
2. Surface preparation: The surfaces of the two metal parts to be joined must be clean, free of oxides, and in good condition. Any surface contaminants or damage can negatively affect the quality of the bond.
3. Pressure: The pressure applied during cold-pressure welding must be high enough to cause the metal to deform and flow, creating a strong

bond. The pressure required depends on the type of metal being joined and its properties but typically ranges from 500 to 1000 MPa.

4. Contact time: The two metal surfaces must be in contact with each other for a sufficient amount of time to allow the metal atoms to diffuse and create a bond. The contact time required depends on the type of metal being joined but typically ranges from a few seconds to a few minutes.
5. Surface finish: The surfaces of the two metal parts to be joined must be smooth and free of defects such as scratches or burrs. The surface finish can affect the quality of the bond and the pressure required for successful welding.

1.15 WHY ARE COPPER RODS JOINED BY COLD PRESSURE WELDING?

Figure 1.21 & 1.22. Cold welded Copper rods

Cold pressure welding is often used for joining copper rods because it can produce a strong, reliable, and uniform bond without the need for heat. Copper is a highly conductive metal that is commonly used in electrical and electronic applications, and cold-pressure welding is well-suited to joining copper wires, rods, and tubes.

One advantage of cold-pressure welding for joining copper rods is that it can produce a bond that is free of voids, porosity, or other defects. This is particularly important in electrical and electronic applications, where the quality and reliability of the joint are critical. Cold pressure welding also does not require the use of filler material, which can be an advantage in certain applications. In addition, because it does not involve heat, cold-pressure welding can avoid any potential distortion or metallurgical changes that can occur during fusion welding.

Thus, cold pressure welding is a simple, cost-effective, and reliable method for joining copper rods that are well-suited to a range of electrical and electronic applications.

CHAPTER – 2

LITRATURE SURVEY

2.1 LITRATURE REVIEW

In this chapter, a complete study of the process was done and all previous attempts to perform weld on different materials were studied thoroughly up to date and results were analyzed.

2.1.1 Cold Pressure Welding-The Mechanisms Governing Bonding.

N. Bay et al. observed the bonding surface under a scanning electron microscope following fracture, demonstrating that the primary mechanisms driving bonding are cover layer fracture and material extrusion through fissures to achieve genuine contact with virgin metal surfaces. A theory for the strength of bonds as a function of surface expansions and typical pressure has been established based on observed bonding mechanisms. This suggests that the surface treatment prior to cold pressure welding (typically involving degreasing and then scratch brushing) is critical to bond strength and should be improved when investigating cold pressure welding processes to ensure uniformity and reproducibility.

2.1.2 Bond criterion in cold pressure welding of aluminium.

T. Tabata et al. colleagues. obtained bonding at lower p values with increasing bulging height. He demonstrated that as the value of p climbed, so did the bond efficiency. The lowest possible value of p for bonding (112 MN m-2) was almost equivalent to the flow-related stress of the base material. Furthermore, when p > 225 MN m-2, the value was independent of p. This indicated that increasing the value of p to a level larger than 225 MN m-2, which was roughly double the flow stress of the base metal, was not required for efficient bonding.

2.1.3 FEM model of butt cold welding.

M. Iordachescu and associates discussed cold welding process beginning terms such as critical deformation, welding significant stress, and welding critical radius. The progression of the welding process was characterised at the elementary level, linking the processes at the macro and microscales and determining the elementary distortion rates that characterise the welding process phases. The effect of distortion on cold weld achievement was investigated experimentally using tensile tests on various joints. The butt cold pressure during the welding of the aluminium bars is produced by the upsetting force when in contact area, the value of the combination of stresses allowing the creation of the sub-grain structures, with dimensions less than 0.3 mm, with the ability of fusing and creating a common lattice. The dependency of the joint's ultimate strength and global deformation was demonstrated. High-quality joints are achievable for larger deformation values when additional technological criteria, such as contact surface preparation or standoff value, are considered.

2.1.4 A Numerical Model for Cold Welding of Metals.

W. Zhany et al. calculated the overlap of surface exposure by first estimating the genuine surface exposure for each metal separately and then combining the two metals. Depending on the type of surface coating, the real surface exposure of each metal is determined. There are two types:

- Cover layer (with contaminated films)
- Contamination films only.

The overlapping surface exposure can now be calculated using the base metal's surface expansion, the ductility of the surface layer, or the threshold surface expansion.

2.1.5 The results of the so far performed investigations of Al-Cu butt cold pressure welding by the method of upsetting.

A scientific description of the processes occurring in both the preparation of surfaces for cold pressure welding and in the welding itself is a requirement for the advancement of the technology for bonding metals and their alloys using cold plastic forming procedures. The initial physical interactions of the surface discrepancies of the two welded materials, and after the first stage of the plastic flattening of those irregularities, result in the formation of new larger irregularities; they are caused by a mechanism of the plastic deformation of grain structure in the surface and subsurface layers.

When the welded surfaces come into contact with each other, the geometric structure of the surface layer along with the subsurface layers is rebuilt. The majority of imperfections are connected to surface preparation technology, and they deform (flatten) most intensively during the preliminary phase of cold pressure welding. The principal irregularities vanish in the final phase. They have less of an impact on the ultimate outcome of cold pressure welding than secondary imperfections.

2.1.6 Interfacial conditions and bond strength in cold pressure welding by rolling.

P. K. Wright et al. demonstrated that unwelded surfaces below the threshold deformation consist of the initial scratch-brushed portions and sections of the underlying base metal that are disclosed but cannot weld due to impurities. The fact that such polluted portions stay unwelded even at larger rolling deformations is a key element of the bonding mechanism described in this research, so that the ultimate strength of the weld is a function of (lie metallic area revealed after the threshold deformation. This notion has been used to compute the area welded, and the findings compare favourably with the proportion of welded area estimated from micrographs of the fracture surfaces. The technique outlined above can be used to build a theoretical link among the strength of the weld and rolling deformation. The weld strength is determined by the metallic area bonded as well as the final breaking strength for every bonded junction, which is influenced by the limiting impact of the unbonded portions along the interface.

2.1.7 Effect of surface roughness on weldability in aluminum sheets joined by cold pressure welding.

Weld strength improves as surface roughness & weld distortion of the linked sheets increase. With increased deformation, the span of bond zones increases. As a result, the length of bond zones affects the weld strength of parts. Then there's the surface roughness effect on welding strength. The hardness of linked parts rises due to localised hardening during deformation in the cold pressure welding process. Tensile strengths of aluminium sheet increase as surface roughness & deformation ratios of aluminium sheets increase. The tensile strength of joined sheets can be described in terms of process factors using a regression equation derived from statistical analysis. Bond formation at the interfaces of sheets linked with Ra 14 5 mm roughness on the surface and a deformation ratio of 60% is demonstrated in the microstructure photo.

2.1.8 Atomic level bonding mechanism in steel/aluminum joints produced by cold pressure welding.

Because of the welding shape, the interface strength may exceed the AW6082 strength in locations where the bonding procedure significantly extended the Fe-Al contact region. There was no evidence of an intermetallic phase. Mechanical testing of such junctions using site-specific tensile experiments indicated that joint strengths grew along the interface up to approximately 60% of constituent strength. Joint strength is extrapolated from SEM pictures of the shattered surfaces to be highest in places that are unavailable for tensile testing but exhibiting the greatest surface enlargements. Aberration adjusted STEM in conjunction with EELS reveals evidence for extensive areas devoid of the two oxides plus intermetallic phases in locations with the greatest surface enlargements.

2.1.9 Mechanical and Metallurgical Properties of Aluminum and Copper Sheets Joined by Cold Pressure Welding.

The tensile strength of the joints rose as the surface roughness and weld deformation ratio of the aluminium sheets improved. Bond formation at the interface of linked pieces is readily visible in micrographs of specimens with a surface roughness of 5 jam and deformed at a deformation ratio of 60%. Joint hardness values are roughly identical at surfaces of sheets with variable surface roughness that are generated under equal deformation. The hardness of Al-Cu joints is comparable to that of aluminium joints. As a result of cold deformation, hardness increases due to localised hardening at the interface. - Fatigue tests revealed that linked sheets could withstand mild variable tensile loads. EDX experiments clearly reveal that Al-Cu joints have an intermetallic compound film at the interface, which has no significant effect on joint strength.

2.1.10 Investigation of cold pressure welding: cohesion coefficient of copper.

Reliable cold-welding conditions, on the other hand, are difficult to achieve because weld initiation necessitates exceptionally clean, practically sheer surfaces. Until now, these circumstances had to be achieved in a high vacuum. According to this cold pressure welding investigation, welds can be produced at considerably less deformation than in a normal environment. Schmid et al. demonstrated in this study that cold welding under a water-based electrolytes is viable and, considering the measured copper grade, nearly similar in quality to a shielding argon environment. Further research is planned to clarify the cohesion coefficient's dependence on more types of deformation, settings such as solvents, and other material arrangements, such as copper to aluminium.

2.1.11 Effect of Interfacial Microstructure on Mechanical Properties of Cold Pressure-Welded Al-Cu Joints Subjected to Annealing.

The butt cold pressure-welded junction for the aluminium and copper plate was subjected to annealing at 543-773 K for 7.2 ks in this work to clarify the impact of the microstructure near the interface on the properties of tensile. Al and Cu grain sizes were refined in comparison to before welding, and work hardening increased hardness along the interface. In the as-welded state, a CuAl2 layer with a thickness of less than 150 nm formed at the interface; yet, it didn't fracture from the junction in the tensile test. Given that the thickness of the $CuAl_2$ layer was so thin, the interfacial strength was thought to be sufficient.

2.1.12 3D Cold Pressure Welded components – From the bonding mechanisms to the production of high strength joints.

Contamination can entirely prevent bonding because it spreads outward throughout the forming process and limits the quantity of bondable surface that is not covered by contamination via revealing the juvenile material. Only a few percentages of bond strength can be optimised if the surface expansion and thus the total proportion from initial to final surface are the same. The varying surface cracking thresholds and number of fractures result in various amounts of form closed bonding, which is much weaker than the attained material closed bond.

2.1.13 On Grain Boundary Sliding and Diffusional Creep.

Raj and Ashby provided a model for the bonding mechanism in CPW in 1971. They proposed that the bonding was caused by the production of significant interfacial tensions between the two metals. As a result, the surface asperities deformed and a wide contact area formed. The metals diffused across the interface as a result of the pressure, producing a metallurgical bond.

2.1.14 Cold Pressure Welding of Aluminum and Copper by Butt Upsetting.

Whenever an appropriate initial height plus a proper drop were chosen in every phase through several stage butt welding, Tabata et al. achieved good bonding at a minor height decrease with a small load. Regardless of the initial height or the number of steps, the bond efficiency is highly dependent on the virgin surface ratio a. At the end of the numerous butt-welding process, the usual pressure at the surface of bonding is relatively low. In bonding of similar metals, sound connecting occurs with nearly identical pressure as the strength of tensile of the monobloc specimen. In dissimilar metal bonding, the pressure corresponds to the tensile strengths of the two metals.

2.1.15. Bonding mechanism of Copper and Aluminum using Cold Pressure Welding.

Karabelchtchikov and Toropov investigated the bonding of copper and aluminium using CPW in 1981. They discovered that increasing the pressure and time of the weld increased the bonding strength. They also discovered that as the pureness of the metals grew, so did the bonding strength.

2.1.16 Effect of surface roughness on the bonding strength of aluminum specimens.

Chandra et al. investigated the consequence of roughness of the surface upon the bonding strength of aluminium specimens in 1995. They discovered that increasing surface roughness boosted bonding strength until some point, after that it began to decline. They also discovered that increasing the contact pressure boosted the bonding strength.

2.1.17 The bonding mechanism in Cold Pressure Welding using molecular dynamics simulations.

Zhu et al. (2013) used molecular dynamics simulations to study the bonding process in CPW. They discovered that the bonding was caused by atom diffusion across the contact. They discovered that when interfacial energy and contact pressure increased, so did bonding strength.

CHAPTER 3

3.1 PROBLEM STATEMENT

- Even though cold pressure welding of copper is attempted earlier, the process parameters influence on the joint is not studied.

- An optimum welding parameter to achieve high quality and high strength joints with favorable microstructure is not evaluated.

3.2 OBJECTIVES

- To fabricate defect free copper rod joints by optimizing cold pressure welding parameters.

- To study the Microhardness and Tensile properties of the welded joints; and characterize the Macrostructure and Microstructure.

CHAPTER 4

EXPERIMENTAL PROCEDURES

4.1 RAW MATERIAL PREPARATION:

Copper in the form of rod is to be joined for this study. Extruded rod of 99% pure EC Grade copper is taken. Standard length of 10 mm rod (fig 1) is purchased after composition analysis. The rod was cut into 20 pieces each of length 150 mm using a cutting machine to produce 10 welded joints for the investigation as shown in fig 2. The rods were then turned down to 8 mm with a tolerance of +0.2mm in a manual lathe machine so that it can be seated in the die. A single point brazed turning tool was employed for this purpose. The ends were then machined properly to ensure full contact during welding.

Grade – C11000 (EC)

Diameter – 10 mm

Length – 1 meter

Quantity – 4 Numbers

Fig 4.1. Raw Material – Standard length copper rods.

Rod Diameter – 8 mm

Rod Length – 150 mm

Quantity – 20 Numbers

Fig 4.2. Copper Rods prepared for joining together.

4.2 SAMPLE DEGREASING AND CLEANSING:

Fresh metal must be exposed for cold pressure welding to take place and hence the sample has to be treated and cleansed before joining. The surface treatment prior to cold pressure welding is critical for achieving bond strength & should be improved to provide uniformity and consistency preceding cold pressure welding operations. Degreasing is done initially, followed by scratch cleansing to eliminate the oxide layer from both edges.

4.3 PROCESS PARAMETER VALIDATION:

The crucial parameters influencing the cold pressure welding process are pressure applied, extent of deformation and number of stages of pressure applied. It is essential to carefully control these process parameters to ensure a successful cold pressure welding operation. The response surface method (RSM) approach based on design of experiments was utilized to build the cold pressure weld joints while determining the best welding variables. According to earlier research, among basic and secondary welding factors, Normal pressure (P) and Extent of deformation / Reduction (R) were considered for cold pressure welding. Working limits were set based on visual inspection by precisely accounting for length reduce, defects, and inadequately bonded joints. The outcomes and discussion sections provide comprehensive data. Normal pressure (P) having a range from 2100 MPa to 2600 MPa and extent of deformation (R) having a range of 15 mm to 70 mm were chosen as welding parameters. To make collecting and analysing experimental data easier, the welding variables' maximum and lowest levels (i.e., values) were encoded as + 1.414 and 1.414, respectively. These encoded variables of any intermediate values (1, 0, and 1) can be determined using the following relationship:

$$Yi = \frac{1.414[2Y-(Ymax+Ymin)]}{(Ymax-Ymin)} \quad (1)$$

Welding Parameters	**Notations**	**Levels**				
		-1.414	**-1**	**0**	**1**	**1.414**
Normal Pressure	P	2200	2258	2400	2541	2600
Extent of Deformation	R	15	23	42	61	70

Table 4.1. Design of Experiments to select the values of process parameters

4.4 THE WELDING PROCESS:

The welding equipment is prepared for use prior to joining the rods. Suitable dies to grip 8 mm rods are installed in the machine. The machine is connected to a hydraulic pressure source and the movement of dies is examined. The alignment of the dies is cross examined to maintain the axis of the rod and increase the cross-sectional area of deformation. The welding set up is shown in fig 3. The desired pressure is set using a pressure control valve and is verified in the gauge. The rods ready to be weld are held in between the dies and clamped. Two such rods are clamped on either side for butt welding them together. The extent of deformation is controlled as per requirement through the position of the rods and the die.

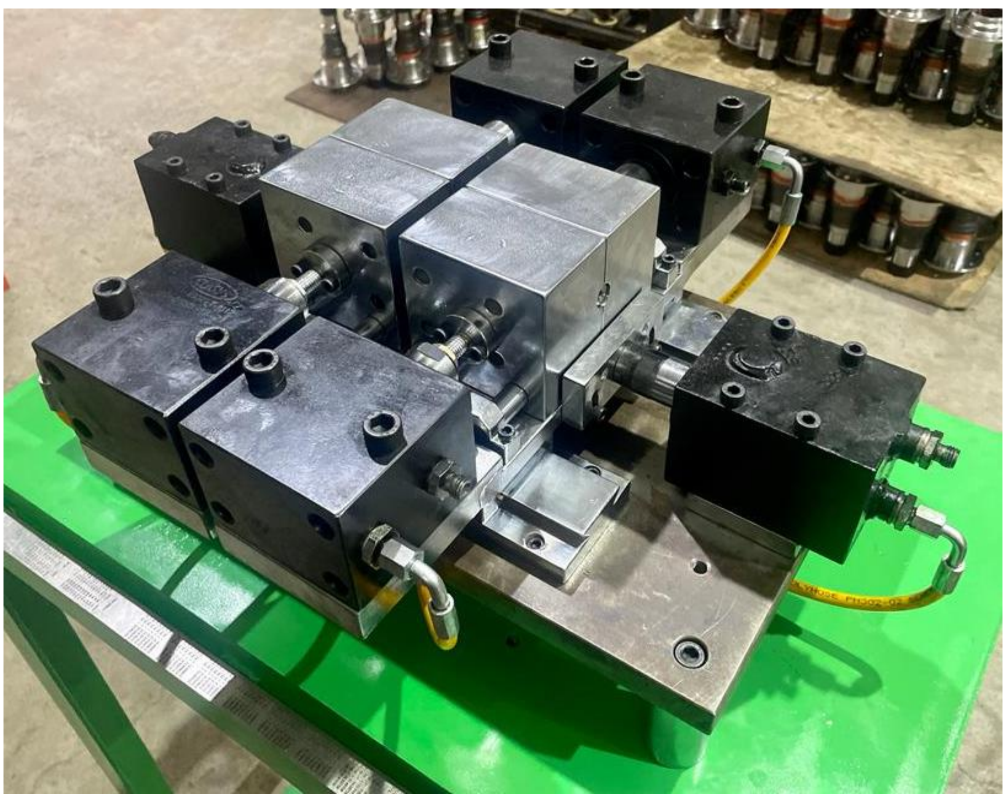


Fig 4.3. The welding equipment along with the dies.

Once the rods are clamped to the dies, they are ready to be exposed to compressive pressure. Each time the rod is compressed certain amount of material flows out as flash. Once a stage of pressure application is complete the rod is released from the die and is clamped again. The load is given in stages as per our requirement by repeating this in cycles. Each stage of pressure application extrudes a band of flash.

Fig 4.4. Welded Samples with flash.

Fig 4.5. Flash expelled during welding for each stage.

4.5 PREPARATION OF TENSILE SAMPLE:

A geometry and the dimensions are determined based on the weld sample and a design for the tensile is prepared. The flash is removed from the weld sample using an abrasive cutter.

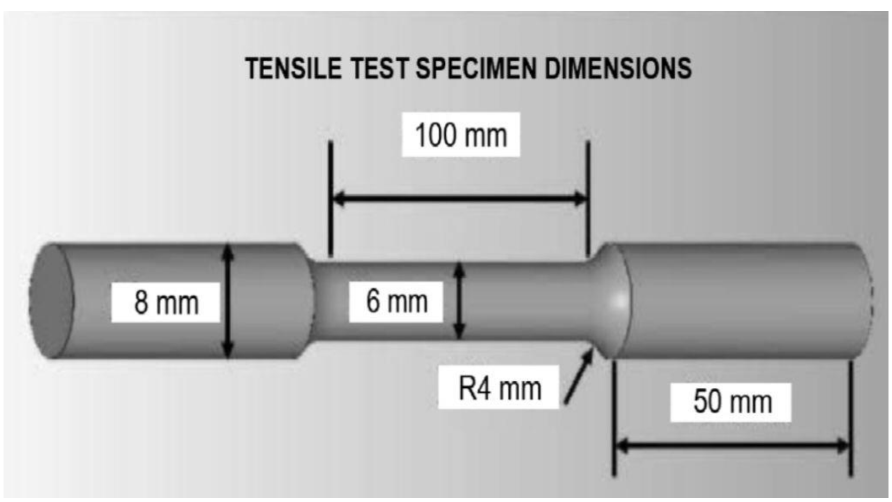


Fig 4.6. Design of tensile test specimen with dimensions.

Using a manual lathe, the weld sample is carefully machined as per the design specification. The sample material should be prepared to ensure that it is free from defect such as cracks, scratches, and contamination. The surface of the sample should be polished to ensure that it is smooth and free from defects that could affect the tensile results.

Fig 4.7. Machining of tensile specimen in a manual lathe.

Fig 4.8. Machined tensile specimen ready for testing.

4.6 TENSILE TESTING OF SAMPLES:

Appropriate grips are selected and are fixed to the ultimate tensile testing machine to be used for the testing. The ultimate tensile testing machine used for testing had a head speed of 1 mm/min and a maximum load of 10 tonne. The specimen was mounted in the grips of the UTM, ensuring that it is centered and aligned with the testing axis. The grips should be tightened to the recommended torque. A constant load is applied to the specimen using the testing machine. Data of the test is recorded using a software and is obtained later for analysis such as yield strength, ultimate strength and elongation.

Fig 4.9. Tensile Specimen after testing.

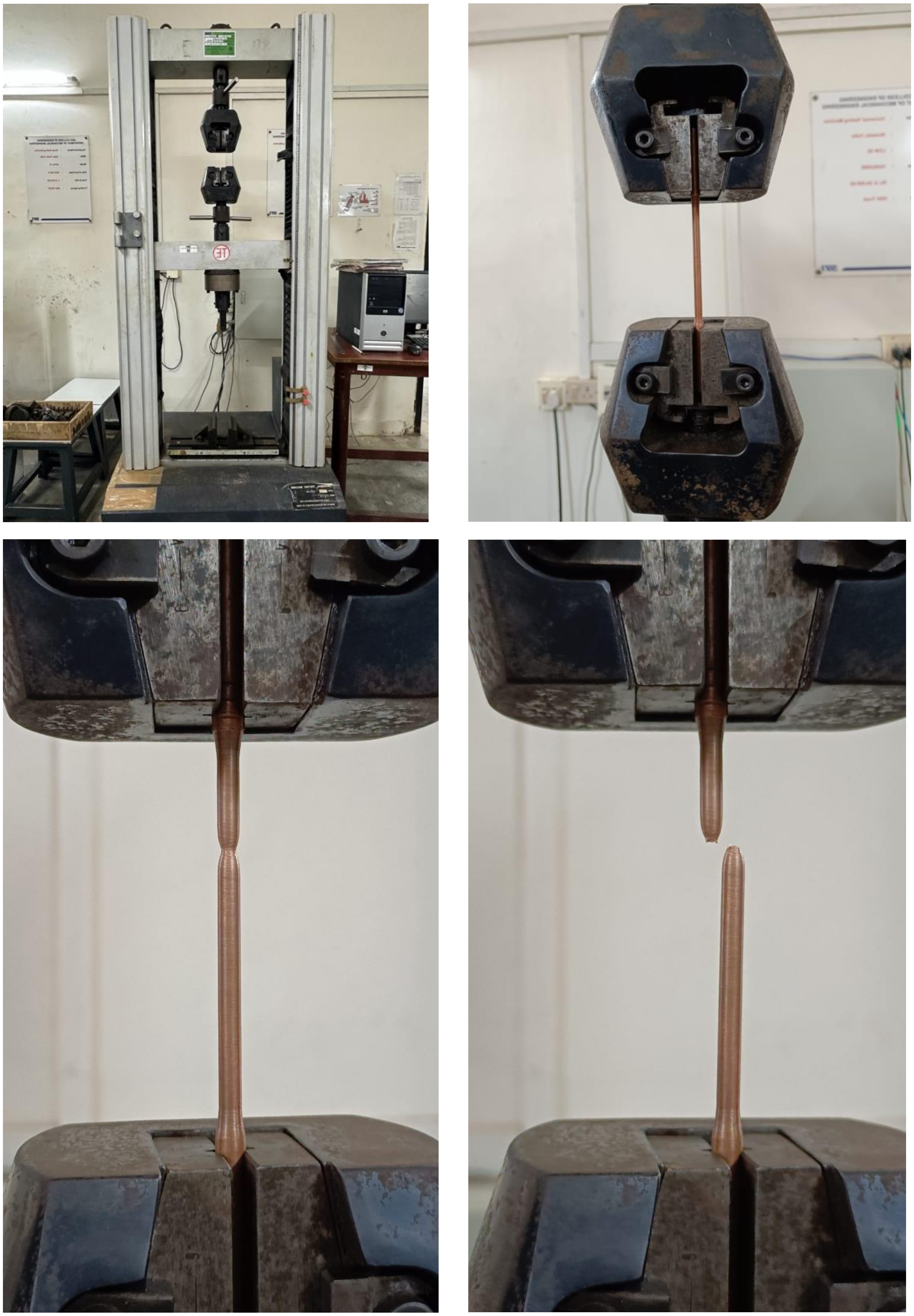


Fig 4.10. a) Ultimate tensile testing machine used for testing, b) Sample held in grips for testing, c) Necking of sample.

4.7 CUTTING, MOUNTING AND POLISHING:

Small piece of the sample is cut off besides the joint from each sample and is used to study the macro and microstructure. This is done manually using a metal cutting saw. The weld samples are vertically cut such that the flash is bisected to examine the cross section of the joint. The flash is cut into halves through wire-cut electrical discharge machining. In this procedure, a thin single-strand metallic wire, in this case brass, is passed through the workpiece before being immersed in a container of dielectric fluid, in this case deionized water.

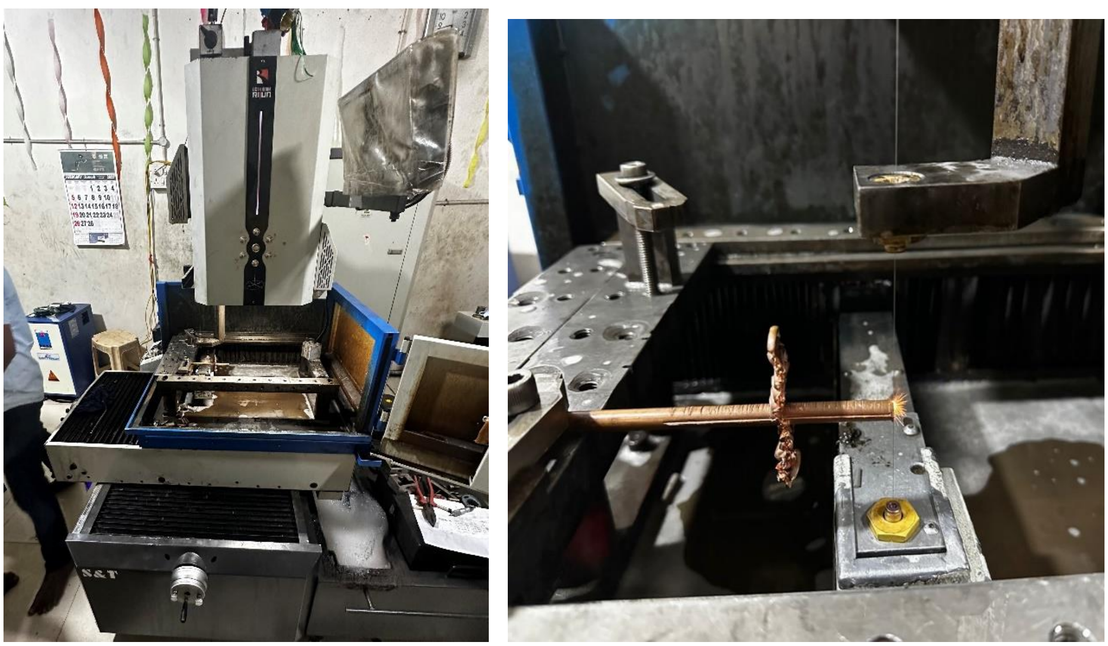


Fig 4.11. EDM wire cutting of sample for examination.

The cut-off sample along with the flash is secured in a holder using a cold mounting resin. This is necessary in order to maintain the structural integrity of the samples during polishing and grinding for further study. The mounted samples are polished, that is removing a thin layer from the sample surface to achive smooth, flat finish using abrasives. Finally, polishing cloth is used to enhance the shine. The polished sample is etched using a solution of 2 g $FeCl_3$ + 5 ml HCl + 95 ml C_2H_5OH to reveal the grains structure.

4.8 MACRO AND MICROSTRUCTURE IMAGES CAPTURING:

A digital camera with lighting capability is used to capture the macro images of all the prepared samples. The microstructure images are obtained using both optical microscope and scanning electron microscope. Lower magnification images are taken using optical microscope and higher resolution images of greater than 500x are visualized through scanning electron microscope. The images are captured using a colour camera attached to the microscope. The imaging equipment is properly calibrated, including setting the correct resolution and lighting conditions.

Fig 4.12. Imaging Equipment used a) Optical Microscope b) Scanning Electron Microscope.

4.9 VICKERS MICROHARDNESS TESTING:

The Micro-Vickers hardness test is used to measure the hardness of the sample at various zones and locations. The Vickers microhardness testing machine is calibrated using a test piece before it is used to test the sample. Dimond indentation is used to evaluate the hardness of the sample at various locations. A load of 0.5 Kg is applied for a dwell time of 15 seconds. The hardness values are noted down region wise and data is curated into plots for analysis regarding the strength, durability and resistance of the sample.

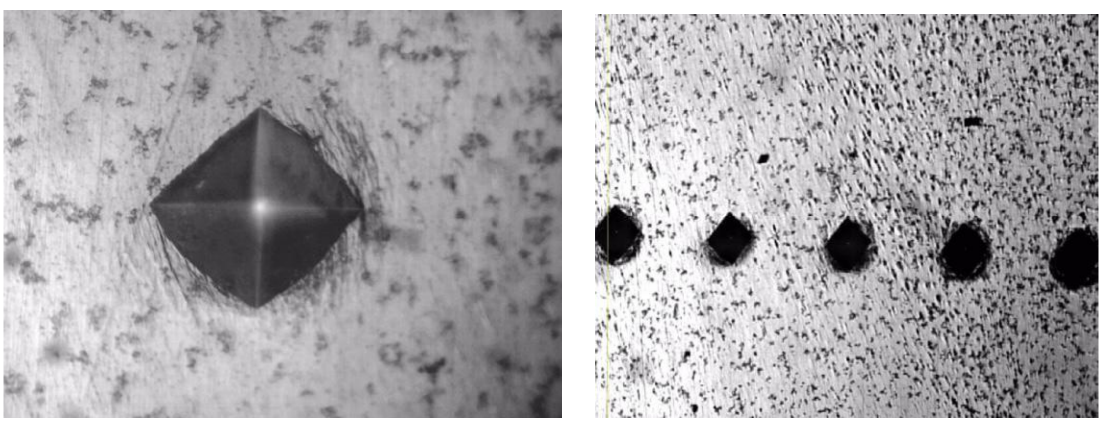


Fig 4.13. a) Dimond indentation, b) Pattern of indentation for hardness measurement.

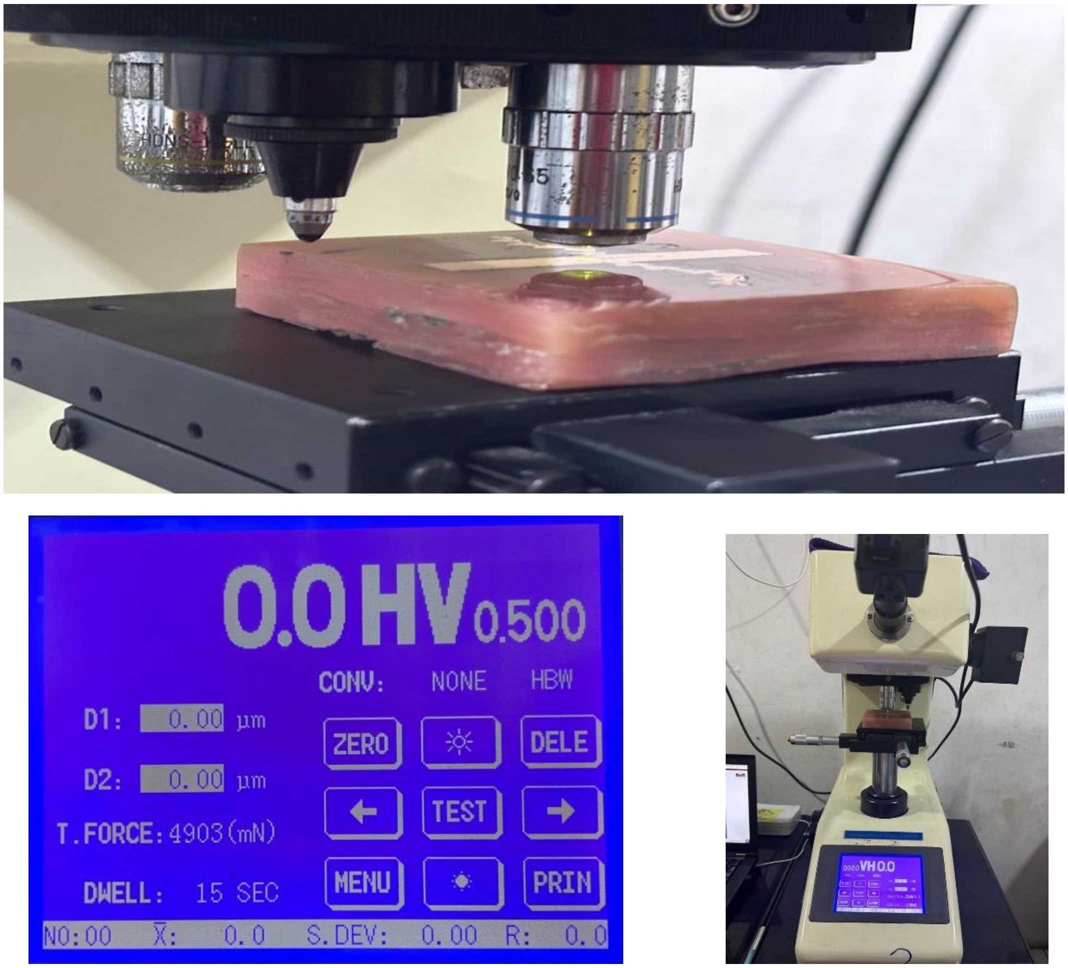


Fig 4.14. Vickers hardness testing equipment.

CHAPTER- 5
RESULTS AND DISCUSSIONS

5.1. OUTCOME OF INITIAL TRAIL EXPERIMENTS:

In multi-stage cold pressure butt welding performed pressure is applied stage by stage initiating a limited deformation each time. The first stage of pressure does not produce any kind of diffusion of materials and the bonding does not start at this stage. This initial stage clears off the oxide layers in the surface and exposes the virgin material to facilitate bonding starting from the second stage of pressure. In all the cases the bonding happened starting from the second stage. As the number of stages increased the extent of deformation is also relatively more as in each stage a certain amount of material is plastically deformed inducing diffusion of atoms into each of the two rods. The reduction in the length or the extent of deformation is indicative of the number of stages used to weld the rods.

The fundamental welding parameters, normal pressure and extent of deformation, regulate the bonding and flaw-free interface features of CPW joints. To conduct CPW tests and manufacture high-quality joints devoid of macro-level defects, an appropriate operating range must be constructed.

5.2. RSM AND CHARACTERIZATION OF CPW JOINTS:

The variation of these factors and their values impacts the deformation distribution and material flow, which in turn influences the microstructure and interfacial properties. This is valid even when the spectrum of welding parameters has been set in order to achieve defect-free junctions at the macro-level.

Std. order	Normal Pressure	Extent of Deformation	Tensile strength
1	-1	-1	155
2	1	-1	171
3	-1	1	299
4	1	1	306
5	-1.41421	0	251
6	1.41421	0	267
7	0	-1.41421	107
8	0	1.41421	304
9	0	0	314

Table 5.1. Output tensile strength response for the cold pressure welded copper joints.

To achieve a high-quality weld joint, the parameters for welding such as normal pressure and extent of deformation have to be set to their optimal levels. Given that trial-and-error techniques are time and resource challenging using design of experiments approaches that are capable of helping in locating the ideal values of welding variables is beneficial.

RSM was utilized in the research in order to discover the optimal welding parameters through carrying out a tensile test on the joints created. Response Surface Methodology (RSM) is a collection of mathematical and statistical methods relating to issue analysis in which numerous independent factors influence a response variable in order to maximize the replies. The ultimate tensile strength is calculated at the output response to identify the optimal values, as shown in table 5.1, and is assumed to be a function of the process's input parameters.

5.3. DEVELOPING RELATIONSHIPS BETWEEN ULTIMATE TENSILE STRENGTH AND THE WELDING VARIABLES OF THE CPW PROCESS:

In statistics, RSM explores the relationships between a number of factors along with one or several response variables. Response Surface Methodology (RSM) is an assortment of statistical techniques for analysing challenges in which an array of independent variables alters a response variable, with the goal of optimizing the response. RSM was used in this study to create empirical connections for the quality parameters of cold pressure welded copper rods in the shape of multiple regression equations. The independent variable was treated as the surface to which an empirical framework was fitted while utilizing response surface methods. The response function, which represents the ultimate tensile strength of cold pressured welded copper rods can be expressed as;

UTS= f (Normal pressure, Extent of deformation)

UTS= f (P, R)

The selected model combines the outcomes of the principal factors as well as the initial-order relationship of all variables. It is a power sequence polynomial, and it can be expressed as follows:

$$UTS = a_0 + a_1(P) + a_2(R) + a_{11}(P)^2 + a_{22}(R)^2 + a_{12}(P \times R)$$

Where a_0 is the mean of the responses, a_1, a_2, and …… a_{22} are the coefficients that depend on the primary and interaction factors.

The coefficients were calculated using the statistical program "Design-Expert" and a central composite rotatable design. The empirical correlations were created after establishing the significant values (at the 95% assurance level). For calculating the ultimate tensile strength of CPW tests, the following types of empirical correlations have been suggested.

Ultimate tensile strength of CPW copper joints

$= 312.40 + 5.70\ P + 69.70\ R - 2.25\ (P \times R) - 26.57\ P^2 - 53.32\ R^2$

5.4. ANOVA RESULTS:

The adequacy of the previously established correlations as shown in table 5.2 was examined using the analysis of variance (ANOVA) approach and the outcomes of 2nd order response surface model were evaluated. Less than 0.5 separates the Predicted R2 from the Adjusted R2, which is regarded as an acceptable compromise for the current conditions. The F-value and P-value of the model are both important, which is a necessary condition. The P value further confirms the significance of the welding variables taken into account for rod joining.

Source	**Mean Square**	**F-value**	**p-value**	
Model	12330.11	23094.15	< 0.0001	significant
P-P	260.23	487.41	< 0.0001	
R-R	38864.73	72793.15	< 0.0001	
PR	20.25	37.93	0.0005	
P^2	4912.91	9201.82	< 0.0001	
R^2	19781.26	37050.04	< 0.0001	
Residual	0.5339			
Lack of Fit	0.1791	0.2239	0.8755	Not significant
Pure Error	0.8000			

Table 5.2. ANOVA analytical results of UTS of the joints.

The extent of deformation is shown to be the primary influence on the ultimate tensile strength in the CPW experiment. The effect of interaction between the two studied parameters is discovered to have a considerable influence on the weld quality attribute.

5.5. THE EFFECT OF WELDING VARIABLES AND DETERMINING OPTIMAL CONDITIONS:

The perturbation plot is used to infer the amount of influence and the way each parameter influences the welding outcome. Figure 5.1 shows the perturbation plot for cold pressure welding with two of the critical parameters normal pressure and extent of deformation considered for the study. The perturbation plot clearly indicates that the most influencing factor is the extent of deformation. Even though the normal pressure applied to facilitate bonding is an important factor, it does not influence the quality in such major way.

Lower applied pressure insufficient to promote flow of material does not involve joining of materials. Once the pressure is sufficient enough to facilitate complete flow of materials into the other rod diffusion take place. Around this level the normal pressure is seen not to have drastic influence. Above this level even if the pressure is increased it does not disturb the output response as the excess pressure above the pressure required to promote complete plastic deformation is not functional.

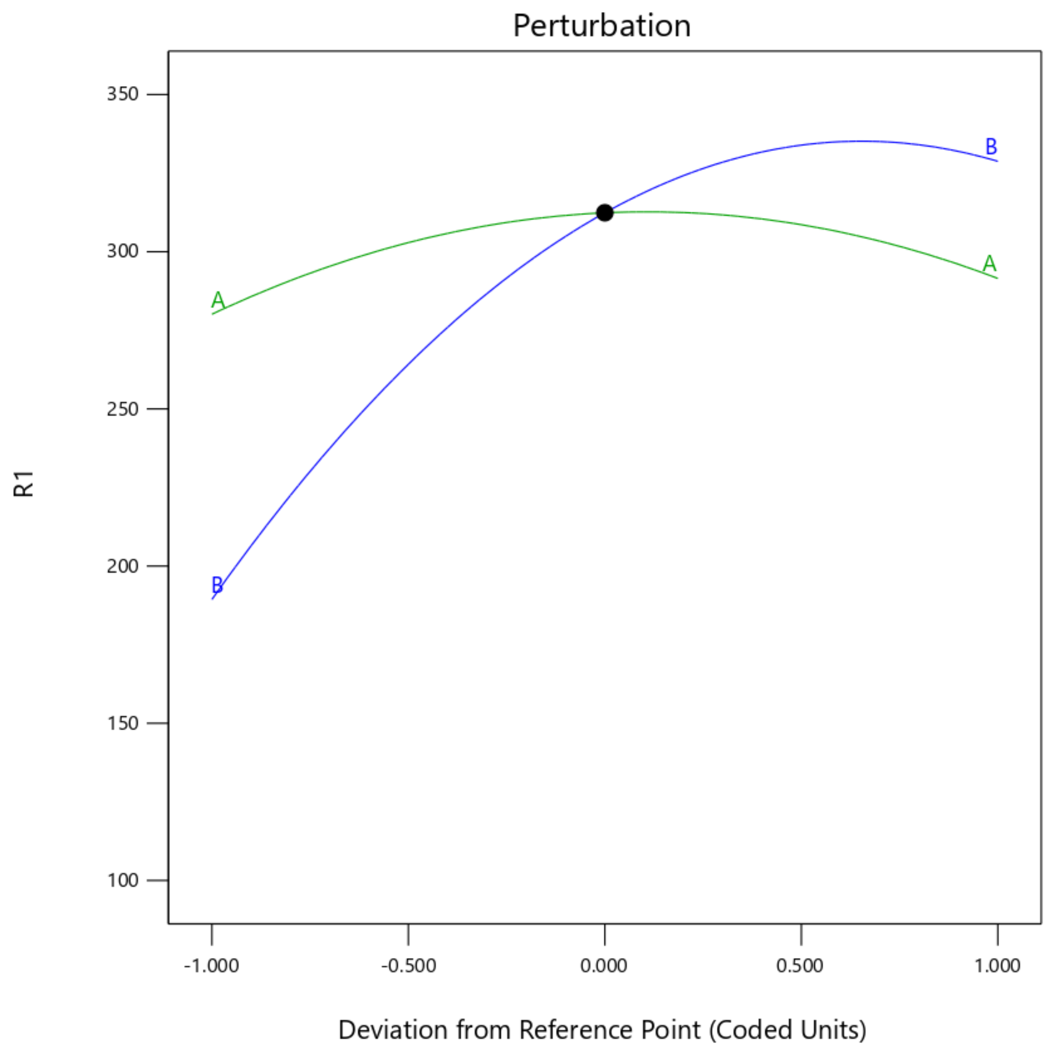


Figure 5.1. Perturbation plot for output response based on the input parameters.

The extent of deformation is the highly influential parameter which governs the bonding. The amount of material that is involved in the bonding is of primary importance. The more the reduction in length, the higher the extent of deformation the more the amount of material is pressurized to undergo bonding. The higher the amount of material flowing across the joint, the more amount of diffusion is taking place which gives scope for high quality bonding. After a certain level of deformation sufficient bonding is achieved between the rods. Any further exposure to plastic deformation leads to reduction in the length of the rod and wastage of material without any abstract necessity. Hence, an increasing level of deformation to abnormal levels have sacrificial effects. Overall, an optimal range of pressure to facilitate complete diffusion of surface material and an exact extent of deformation to achieve necessary bonding leads to an optimal input as per the plot. These variables affect the strength of the joints as measured above.

The interaction between the two critical parameters are studies using a contour plot. The contour plot in the figure 5.2 represents the mutual interaction between the normal pressure (A) and the extent of deformation (B) and its effect on the output response. The elliptical interaction plot shows that there exists recognizable interaction between the two parameters influencing each other. As the extent of deformation increases the effect of pressure on the bonding is minimized as the increased material flow on each stage compensates for the pressure. This relation is considered and optimal parameter is inferred from the plot against the coded values 0 and 0.706 for pressure and extent of deformation respectively.

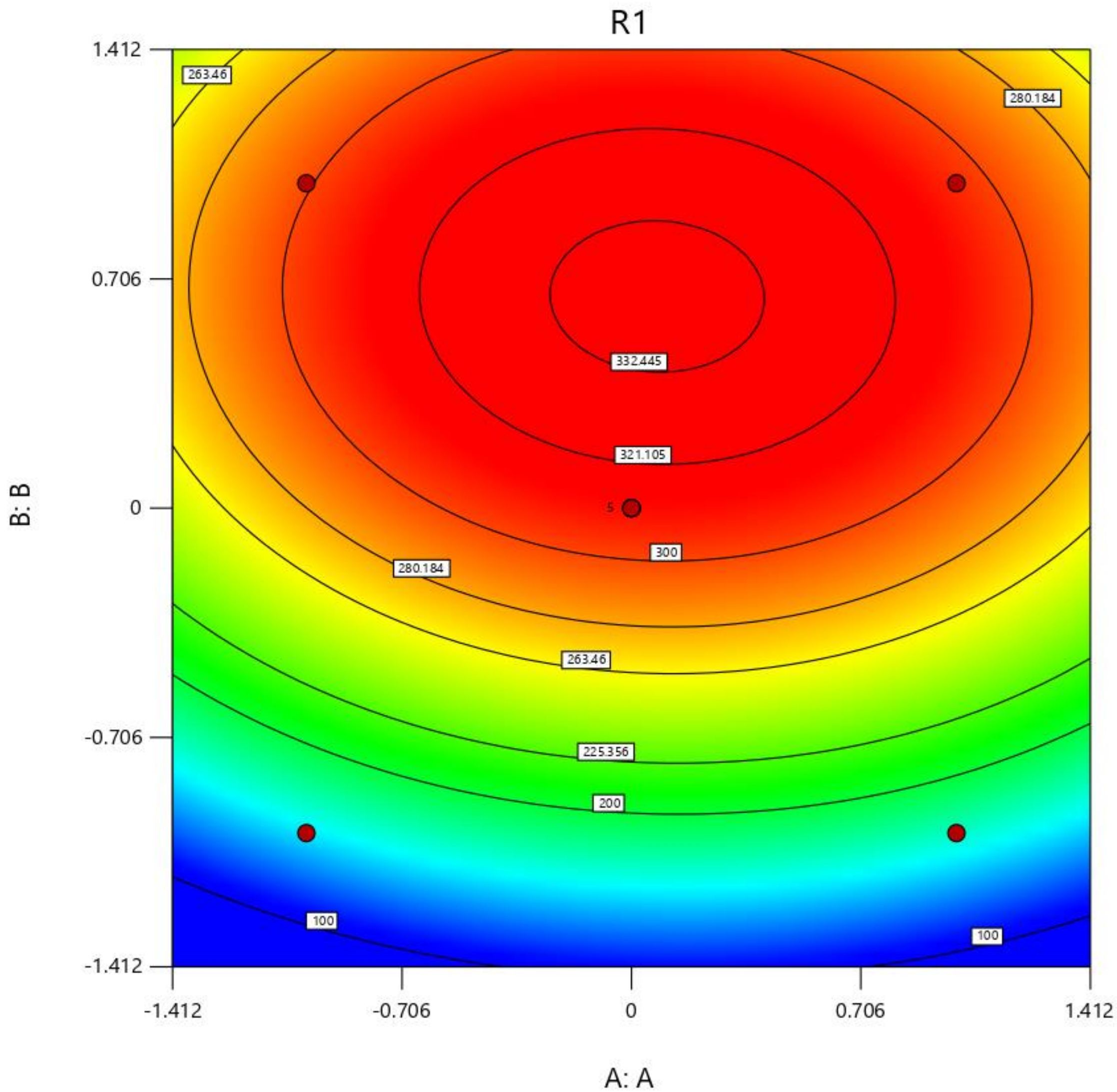


Figure 5.2. Contour plot revealing the interaction between the parameters.

The optimization functionality of the design-expert software was applied to determine the best input process variables values for maximum tensile strength of the cold pressured welded copper joints. According to the numerical optimization results and the contour plots for the developed empirical correlations, the best possible parameters are 2400 MPa of normal pressure applied and an extent of deformation of 56 mm.

5.6. MACROSTRUCTURE INFERENCE OF THE JOINTS:

The macrostructure of the joints shows the evolution of different zones with varied grain size and orientation. The zones identified from the observation of the macro images shown in figure 3 is the bonding zones, deformation zones and the base metal. The bonding zone is the region where the two metals have bonded together due to the high interfacial pressure and deformation. The microstructure of this zone exhibits a fine-grained structure and some evidence of atomic diffusion across the interface which is later investigated using optical microscope images. The region immediately adjacent to this is the deformation zones. This is where the metal has undergone significant plastic deformation due to the pressure applied during welding. This zone typically has a fine-grained structure which has dislocated severely. Moving away from this region the base metal is seen, that is the original metal before welding which has unchanged grains larger in size.

The macrostructure evolved shows variation according to the input parameters used to perform the weld. In all the case, the bonding zones thickness remained the same, a narrow region in the interface. While, the deformation zone for each sample varied with the pressure and deformation it was exposed to. The sample exposed to higher deformation had more deformed zone while lesser extent of deformation had feeble deformation zone. The flash in the macro is representing the number of stages acted upon and it is indicative of the extent of deformation.

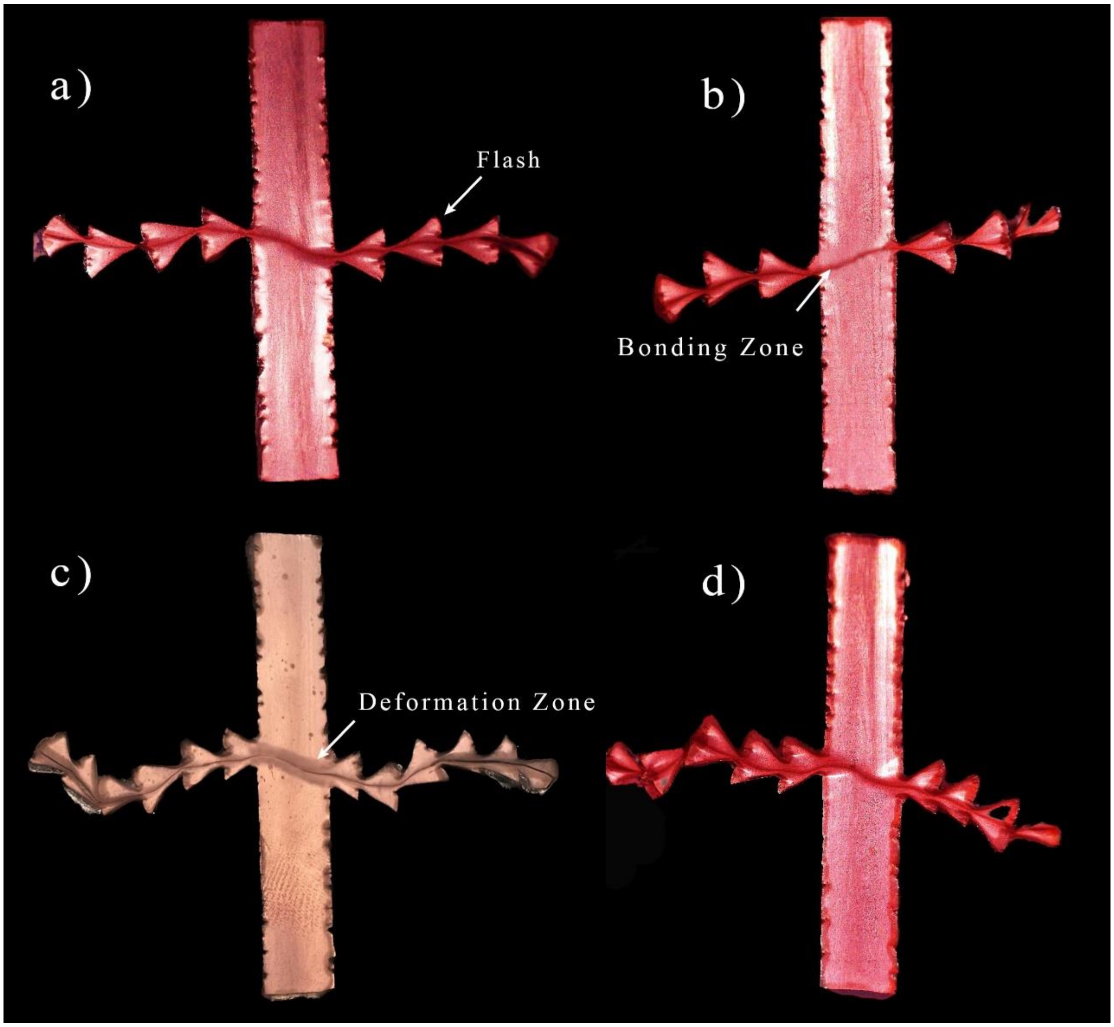
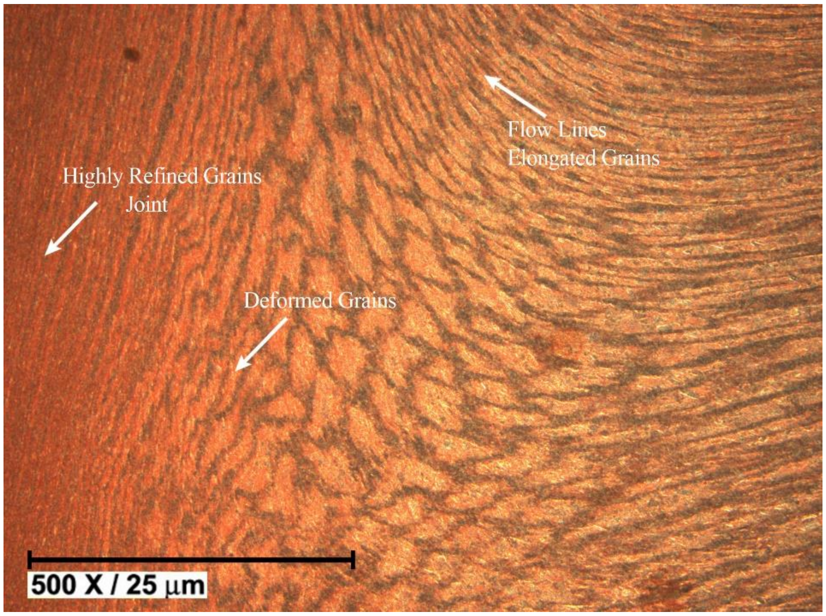


Figure 5.3. Macrostructure images represting different zones.

5.7. MICROSTRUCTURE EVOLUTION OF DIFFERENT WELDS:

Investigation of the microstructure using optical microscope reveal the flow pattern of the grains on application of constrained pressure. The grains have undergone severe dislocation due to exposure to strain and grain have elongated and their width has narrowed as shown in figure 5.4. The dislocated grain flows with pattern towards the joints into the flash away from the axis of the rods on both the sides. As the effect of pressure decreased as we move away from the join the grain size is seen to increase leading to the base metal.



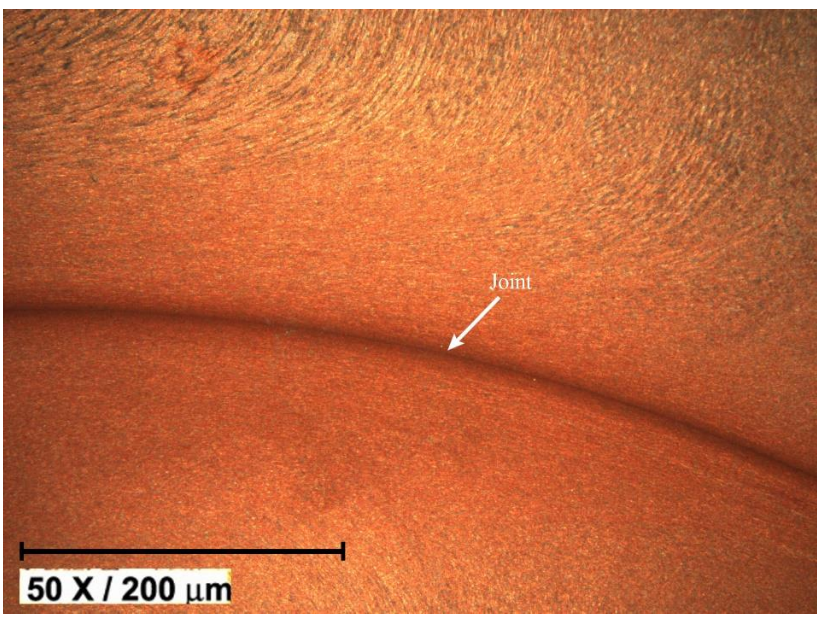


Figure 5.4. Optical microscope images showing the flow pattern of grains.

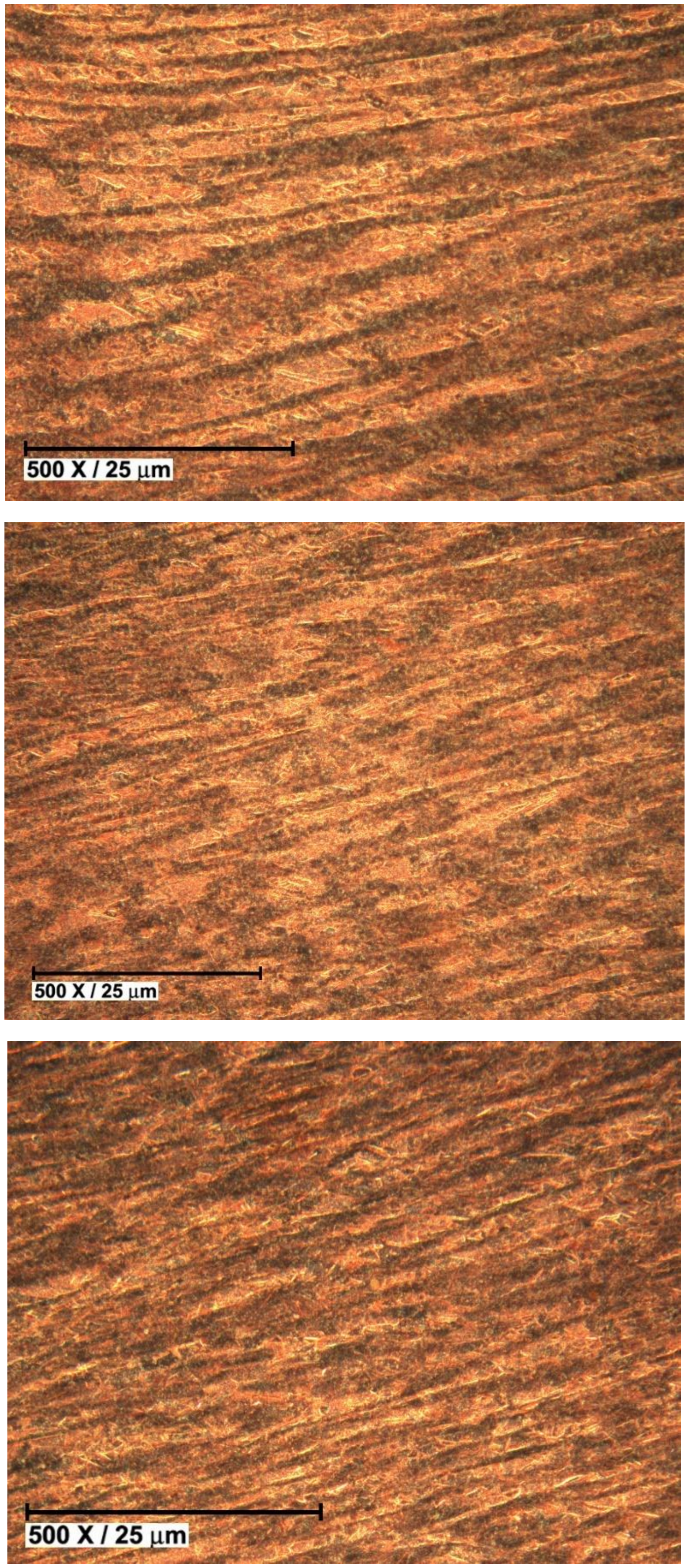


Figure 5.5. Grains in deformation zones for different parameters used.

Investigation of the microstructure using optical microscope reveal the flow pattern of the grains on application of constrained pressure. The grains have undergone severe dislocation due to exposure to strain and grain have elongated and their width has narrowed as shown in figure 5.5. The dislocated grains flowing with a pattern towards the joints into the flash away from the axis of the rods on both the sides. As the effect of pressure decreased as we move away from the join the grain size is seen to increase leading to the base metal.

The grain size, flow pattern and the dislocation are seen to vary with change in parameter which is observed through figure 5.5. The change in parameters effect on the microstructure can be utilized to arrive at an optimal welding condition. The grain size of deformation zone for different parameters used are measured to vary between 5 μm to 15 μm. An increase in the normal pressure applied, increases the strain on the grains which further decreases the size of the grains in the deformation zone.

5.8. MICROHARDNESS, STRENGTH AND FAILURE ANALYSIS:

The hardness of the fabricated joint across all direction is represented through a contour plot shown in figure 5.6. There is zone wise difference in the hardness and across the zone there is minimal, insignificant variation in hardness. The maximum hardness is attained in the bonding zone which reaches up to 138 Hv. The peak hardness at the bonding zone gradually decreases as we move into the deformation zone on the either side. In the deformation zone the hardness ranges from 122 Hv to 129 Hv due to strain hardening. Moving further away from the joint to the base metal the hardness settles at a default value of 110 Hv. The increase in the hardness value in the deformation and the bonding zone is due to the effect of plastic deformation on the grains.

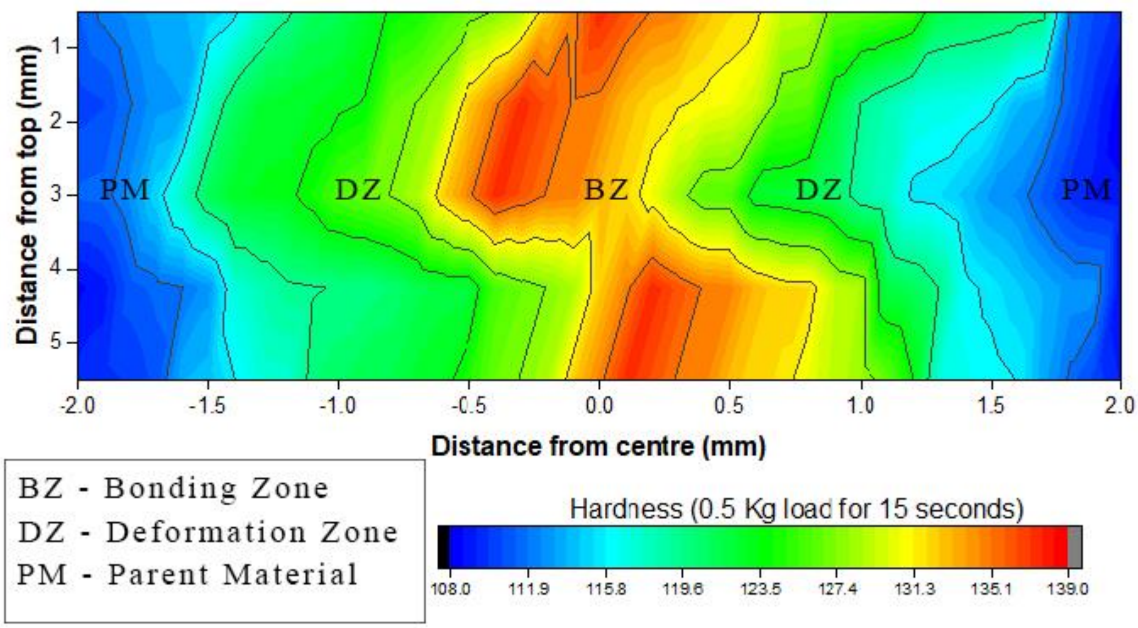


Figure 5.6. Contour plot representing the hardness across the joint.

The peak hardness in the cold pressure welded joint is observed to vary based on the parameters used to perform the weld. The variation in the peak hardness is plotted in figure 5.7 for optimal welds performed and minor difference is noted between joints. The hardness variation is seen to vary with the grain refinement. As pressure increases the strain on the grain is higher which increases the grain refinement leading to higher hardness in the joint.

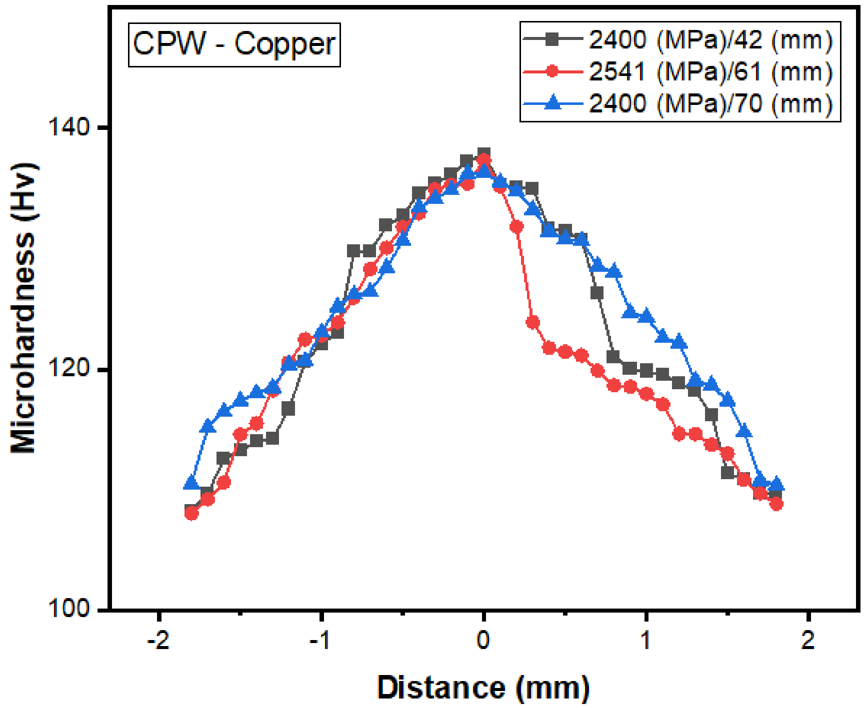


Figure 5.7. Plot showing variation of hardness for different joints.

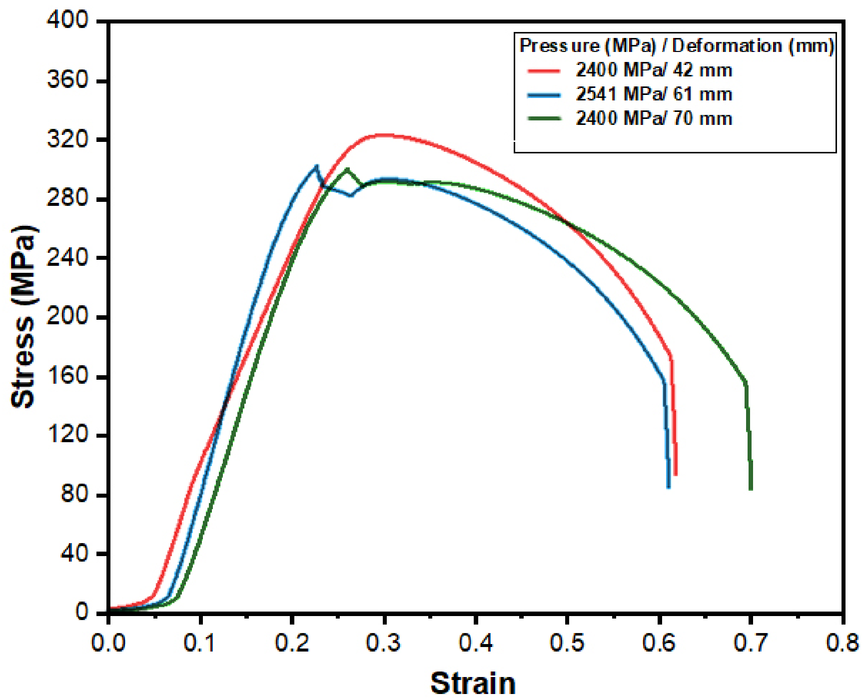


Figure 5.8. Ultimate tensile strength of distinct joints.

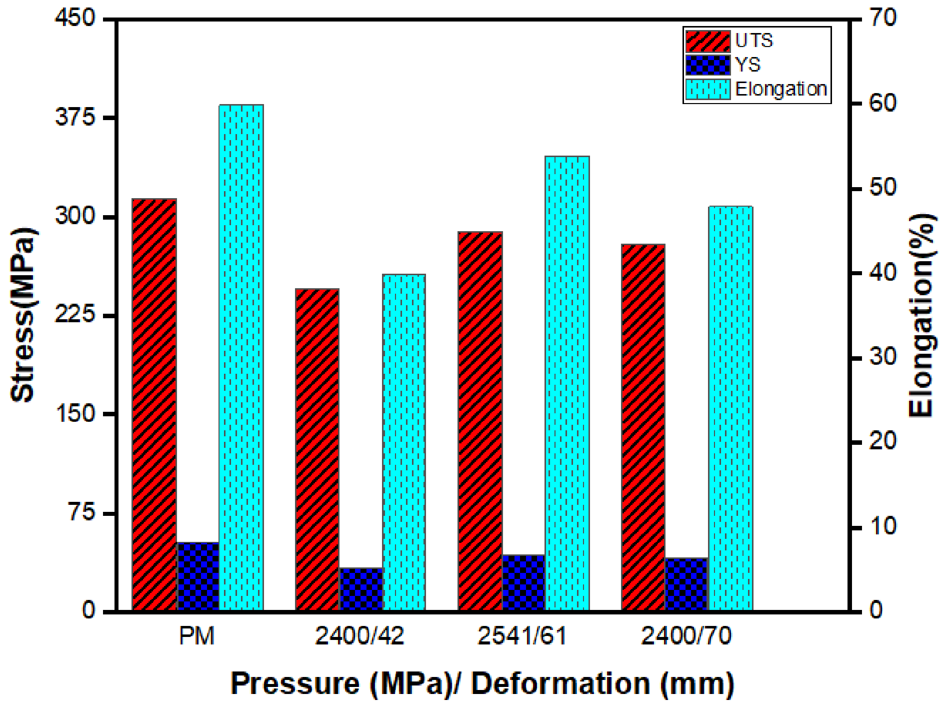


Figure5.9. Relative mechanical strength and elongation of distinct welds.

The increase in hardness increases the strength of the joints. The strengthening of the joints prevents the failure to occur in the joints. Instead, the failure happens along the axis in the parent material when weld is done with optimal parameters. In such optimal conditions the ultimate tensile strength of the joints is above 300 MPa reaching a maximum of 314 MPa as shown in the figure 5.8. On the other hand, on occasions when the pressure is not sufficient or deformation is far lesser to initiate bonding the failure takes place in the joint with low tensile strength.

The elongation of the weld samples is recorded to be around 40% to 55% in the figure 5.9. There is only a slight reduction in elongation as no heat is involved in the process retaining its ductile property. The slight variation in elongation of the joints could not be accounted with both the variation in pressure and deformation whose effect is negligible.

CHAPTER – 6

CONCLUTION

A comprehensive examination of the microstructure and mechanical characteristics was conducted to comprehend how the normal pressure and the extent of deformation influence cold pressure welded copper joints. Following is a summary of the primary finding:

- In the multi stage upsetting carried out, the first stage was responsible for clearing the surface imperfections while from second stage onwards the bonding is initiated due to diffusion.
- The normal pressure and the extent of deformation were found to significantly influence the weld quality, among them comparatively extent of deformations effect was far more evident.
- A relation between the output response, the ultimate tensile strength and the input welding parameters was studies using response surface methodology. Interaction among the two parameters was discovered to optimize the factors.
- The optimum welding variables to obtain high strength joints were evaluated as normal pressure of 2400 MPa and the extent of deformation of 56 mm.
- The macrostructure inspection showed three different zone in the joint namely the bonding zone, deformation zone and the base metal. The bonding zone is a narrow region with highly refined grains. The deformation zone has elongated and strained grains which are dislocated.

- The flow pattern of the grains in the deformation zone was visible through the microstructure. The grain size of the deformed grain size varied according to the welding variables between 5 µm and 15 µm. The higher the pressure the more refined is the grain size. Similarly, when the extent of deformation increased the width of the deformed zone increases.
- A hardness increase was apparent near the weld region. The peak harness was attained in the bonding zone. A maximum harness of 138 Hv was recorded based on the parameter. The extent of grain refinement directly influenced the hardness evolved.
- The increase in the hardness near the joint induces a strengthening effect around that region. This prevents failure near the joint in weld produced using optimal parameters where the ultimate tensile strength was above 300 MPa and reached a maximum of 314 MPa.
- The elongation of the weld was in the range of 40% to 55% which is a only a slight reduction from the parent. The ductile property was not as much affected as there was not heating involved.

CHAPTER 7

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