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Experimental and Process Optimization Study on Thermal Stress Reduction in TiC–Steel Brazed Joints Using Polymer-Derived Composite Interlayers

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Abstract

In this, an experimental investigation aimed at reducing crack formation due to thermal stress in TiC-steel brazed joints through optimization of key process parameters is presented. The primary objective was to develop an integrated and reliable brazing strategy by examining the effects of filler material selection, brazing gap, cooling conditions and type of flux. In this study, polymer-derived composite interlayers were developed through controlled synthesis and nanocomposite engineering to mitigate residual stresses. Advanced characterization techniques were employed to correlate molecular structure, interfacial properties, and thermal behavior with stress reduction efficiency. The incorporation of functional and nanostructured fillers improved thermal conductivity, mechanical compliance, and stress redistribution capability. Experimental results demonstrated significant reduction in crack formation and improved joint integrity under thermal cycling conditions. Furthermore, sustainable and bio-based polymer approaches were explored to enhance environmental compatibility without compromising performance. The developed interlayer system exhibited superior thermal fatigue resistance and reliability, highlighting its potential for advanced structural, energy, and high-temperature engineering applications. Earlier methods of using silver-based filler materials and powder flux caused a number of problems, including oxide formation at the joint interface, high thermal stress (up to 85-90%) reduced tensile strength, and poor service performance of TC chisels. The results showed a significant reduction in thermal stress levels by about 10-15%, as well as improved joint integrity and elimination of crack formation. Optimal brazing conditions were identified in the temperature range of 890-920°C, with a joint clearance of 0.4-0.6 mm and controlled furnace cooling. The improved performance is attributed to the ability of the Cu-rich filler material to accommodate the thermal diffusion gap between TiC and steel.

Keywords: Brazing, Composite interlayers, Multiscale modelling, Polymer-derived interlayers, Sustainable polymers, Thermal Stress

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INTRODUCTION

Brazing is a widely used process of joining dissimilar materials, especially for carbide-steel systems in industrial tooling applications. However, the thermal diffusion difference between TiC and steel poses significant challenges, resulting in residual stresses and cracks. Although studies exist that focus on filler materials and brazing techniques, there has been limited research on the combined effect of brazing gap, cooling rate, and flux composition. The joining of dissimilar materials such as titanium carbide (TiC) and steel has attracted considerable attention due to their combined advantages in structural, aerospace, and energy applications. However, significant differences in thermal expansion coefficients and mechanical properties have resulted in the development of high residual stresses during brazing, often leading to interfacial failure and reduced service life. Conventional approaches to mitigate these stresses have shown limited success, necessitating the development of advanced interlayer materials with tailored properties.

Recent advances in polymer chemistry and composite materials have enabled the design of polymer-derived interlayers with controlled architecture, enhanced functionality, and tunable thermomechanical behavior. The integration of nanocomposites, supramolecular structures, and functional polymers has further improved stress accommodation and interfacial bonding characteristics. In particular, polymer-derived ceramic and composite interlayers have demonstrated promising potential in reducing thermal mismatch through improved compliance and energy dissipation mechanisms.

Comprehensive characterization methods, including spectroscopy, thermal analysis, and microstructural evaluation, have facilitated a deeper understanding of structure–property relationships governing interlayer performance. Additionally, multiscale modeling and simulation approaches have been increasingly utilized to predict thermal stress evolution and guide material design. Processing techniques such as controlled curing, extrusion, and thermal treatment have also played a crucial role in achieving defect-free and uniform interlayer formation.

Sustainability considerations have further driven interest in renewable and green polymer systems, enabling environmentally responsible material development without compromising functional performance. Moreover, advances in composite engineering, including nanofillers and hybrid materials, have significantly enhanced thermal conductivity, mechanical strength, and resistance to thermal fatigue.

In this context, the present study focused on the experimental development and process optimization of polymer-derived composite interlayers for thermal stress reduction in TiC–steel brazed joints. By integrating material design, advanced characterization, and modeling approaches, this work aimed to establish a comprehensive framework for improving joint reliability and performance in demanding engineering environments.

The basic principle of brazing is Capillary action causes the filler material to flow or melt into the gap created by joining two base parts, with a lower melting point than the base material as shown in figure 1. Brazing is a joining process that requires two parts of metals or non-metals to be joined. Brazed joints have greatest tensile strength. they are offer stronger joint than the two metals being bonded together. Due to the fact that brazed joints do not melt, they are not distorted and retain their original properties despite being exposed to gases and liquid. They are also resistant to vibration and shock. As brazed joints have an extremely clean, good finished appearance, they are usually used to manufacture fixtures, heavy construction equipment, tools, and high-quality goods. Brazing is the process which is economical & fast, it requires low temp for performing and it is highly choose into automation and lean production manufacturing. Some filler materials are not suitable for some brazing processes (eg. in vacuum brazing Zinc filler material are not used). While brazing operation carried out first up all design the joint it means the identify the gap between to product for flowing the filler material. clean the both products to remove dust, oil, grease, oxidation etc. for brazing accuracy the brazing process performs in vacuum. Then heat the product that time insure the position of products. When this product heats well then, the apply the filler material into the gap. This material melts and fill the gap in between two products. For melting this filler material can use the flux powder. Now this assembly kept for cooling. It many forms of cooling like natural cooling, furnace cooling, forced cooling with fan etc. this is simple way to brazed the product [1].

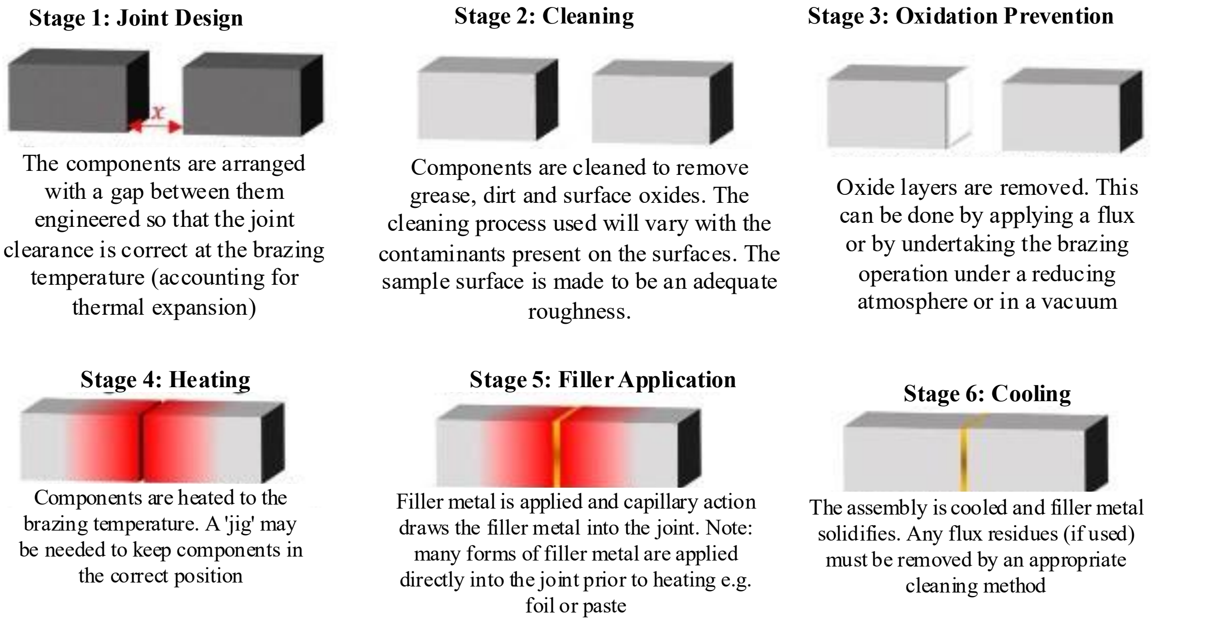

Figure 1. A diagrammatic representation of the 6 main stages required for a brazing operation, stages will vary with each specific brazing process

Demonstrated strong agreement with RSM predictions (<7 % deviation), confirming the optimized coating's superior wear resistance. Metallurgically bonded diamond particles during wear processes served three critical functions: load-bearing support, abrasive cutting resistance, and modification of abrasive particle trajectories. [2] concluded that the key challenges are difficulties in simultaneous processing of both hard and binder phases without deteriorating their properties in the formed composites, as well as great residual stresses, causing the formation of cracks. [3] presented perceptions of the microstructure of treated steel and solidified carbides brazed with the sandwich combination Ag-Cu-Zn-Mn-Ni with a copper center in a 1:2:1 proportion. The filler metal comprised of 10 % less silver and 10 % more copper than the silver-based compound Ag449.The brazing system was done utilizing a brazing light with the fluoride-chloride motion. [4] expressed brazing is a pragmatic subject and has maybe focused more on the what than the why filler metals are created for explicit applications and evaluated against the significant models for each situation, while key comprehension of the cycles is less investigated. [5] explained two-parameter fracture analysis tool. Compared with the traditional fracture mechanics method, CZM avoids the stress singularity of the crack tip in the linear elastic fracture mechanics. [6] presented strength of brazed joints is of great significance for plate-fin heat exchangers. He explained, the crack propagation of SS304/BNi-2 brazed joints was investigated by both experiments and numerical simulations. [7] discussed finite element method (FEM) is the most commonly used. The grid division of the crack tip in FEM has a great influence on the simulations of the crack propagation process. [8] explained extensive audit about the cutting-edge progresses relates with the impacts of filler and intensity therapy on the physical and mechanical properties of the brazed joint between carbide tip and steel under light brazing. [9] discussed a condition of the inquiry concerning stresses in brazing joints of various physical and mechanical properties was assessed as well as probability of their lessening because of purpose of various procedures from innovative investigations to mathematical techniques. [10] presented the acceptance brazing of TiC based cermet with Ni-Mo and Fe-Ni cover stage and Cr3C2 based cermet with Ni fastener to underlying and treated steels under vacuum and cools. Expansion in the surface harshness after mechanical metallizing and non-uniform appropriation of Ti on the treated surfaces were noticed. [11] discussed hard metals have incredibly high hardness and wear opposition, which render them ideal for applications, for example, metal-cutting apparatuses, rock-boring instruments, and modern wear-safe parts like kicks the bucket, punches, and seals. He audited a few techniques accessible for the joining of hard metal to steel, and talks about the benefits. [12] This study investigated the tribological behavior of aluminum reinforced

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with Al2O3 and graphene by powder metallurgy, focusing on crystal structure, mechanical properties, and dry abrasion resistance. Advanced techniques such as optical microscopy and SEM analyzed the microstructure and scratched surfaces. Four cylindrical preforms containing varying amounts of Al2O3 were sintered at different temperatures. The pin-on-disk tester measured the loss due to friction at a distance of 4000 meters at 300 rpm, while the hardness was measured using the Rockwell tester. The results showed that higher concentration of Al2O3 and increased sintering temperature increases the hardness and reduces erosion. SEM images revealed a uniform distribution of Al2O3 in the aluminum matrix, with 5% Al2O3 improving density and performance at low temperatures, reducing friction and corrosion compared to 1% and 3%. Overall, this integration improved mechanical and corrosion resistance. [13] Outlined brazing is a joining cycle used to get heterogeneous congregations between various materials, for example, prepares, irons, non-ferrous metals, pottery and so on. The brazing procedures utilized were oxygen-gas fire and enlistment joining. [14] given the consequences of joining tungsten diminished actuation ferritic martensitic (RAFM) steel RUSFER EK-181 by high-temperature brazing utilizing quickly set foil-type filler in view of copper-titanium (Cu-Ti) composites. [15] reviewed several widely used temperature measurement methods and show how they can be applied to temperature monitoring during material removal. Since there is little documentation on measurement uncertainties as relates to material removal, this paper outlines the physics of each method, detailing the sources and evaluation of uncertainty. [16] Fiber-reinforced polymer composites, especially those that include graphene nanoplatelets (GNPs), are growing in popularity due to their durability and sustainability. This study explored how spindle speed and feed rate of different weight percentages (0.125, 0.25, and 0.375 wt%) of GNPs affect the losses during drilling of carbon fiber reinforced polymer (CFRP) composites. The findings show that adding up to 0.25 wt% graphene improves the mechanical and machining properties of CFRP composites, resulting in optimal values for surface roughness, torque, thrust force, and delamination factors. [17] examined the properties of joining refractory metals, which are infamously hard to braze because of their high melting temperatures, robust oxide coatings, and restricted solubility with common filler metals. Similar to this, [18] concentrate on hard materials and refractory metals in relation to high-temperature applications. Industry knowledge and best practices are further consolidated in the American Welding Society's (AWS) [19]. One of the founding books in the field is [20], which provides a thorough overview of brazing concepts, metallurgy, joint design, and process parameters.

PROBLEM STATEMENT

The brazing of dissimilar materials such as titanium carbide (TiC) and steel has been widely used in high-temperature structural and wear-resistant applications. However, a significant mismatch in coefficients of thermal expansion and elastic properties between TiC and steel has resulted in the development of high residual thermal stresses during cooling after brazing. These stresses have often led to interfacial cracking, delamination, and premature joint failure, thereby limiting the reliability and service life of such assemblies.

Conventional interlayer materials, including metallic foils and simple composites, have shown limited effectiveness in accommodating thermal mismatch due to insufficient compliance and poor stress redistribution capabilities. Additionally, existing approaches have not adequately addressed the optimization of processing conditions and the role of interlayer microstructure in controlling stress evolution. The lack of integration between polymer chemistry, composite design, and process engineering has further restricted advancements in this area.

Therefore, there has been a critical need to develop advanced interlayer materials with tailored thermomechanical properties, improved interfacial bonding, and enhanced stress relaxation behavior. In particular, polymer-derived composite interlayers have emerged as a promising solution, but systematic experimental studies combined with process optimization and structure–property correlation have remained insufficient. Addressing these gaps is essential for achieving reliable, high-performance TiC–steel brazed joints for demanding engineering applications.

OBJECTIVE

The main objectives of work given below:

1. To synthesize and develop polymer-derived composite interlayers with tailored composition and architecture for TiC–steel brazed joints.
2. To investigate the effect of interlayer material properties, including thermal conductivity and mechanical compliance, on thermal stress reduction.
3. To optimize brazing and interlayer processing parameters, such as curing temperature and thermal cycles, for uniform and defect-free joint formation.
4. To study the role of nanofillers and functional additives in enhancing interlayer performance and stress accommodation.
5. To assess the mechanical performance, including crack resistance and thermal fatigue behavior, of brazed joints.
6. To establish structure–property relationships governing interlayer effectiveness in stress mitigation.
7. To explore sustainable and bio-based polymer systems for environmentally friendly interlayer development.
8. To develop an optimized framework for improving the reliability and service life of dissimilar material brazed joints.

METHODOLOGY

Polymer-Based Stress Buffer Layer

To reduce the thermal mismatch stress, a polymer-based thin stress buffer layer can be inserted between the TiC insert and the EN24 steel before brazing. This interlayer acts like a flexible transition zone, which absorbs the different diffusion and contraction that takes place between the heating and cooling cycles. High-performance polymer-derived coatings such as polyamide, epoxy-ceramic composites or phenolic resins reinforced with nano-silica are suitable options due to their thermal stability and good adhesion to both ceramic and metal surfaces. During the cooling process, the polymer composite layer redistributes the local stresses, reducing the stress concentration at the brittle TiC interface and preventing cracking. As a result, the rigidity, durability and service life of the brazed connection are significantly improved. Characterized polymeric interlayers using spectroscopy and molecular weight analysis, correlating structure–property relationships with observed reductions in residual thermal stresses achieved. Applied multiscale modelling and constitutive theories to predict stress evolution, integrating machine learning for improved structure–property quantification accuracy in systems. The detail methodology given below:

Materials Selection and Preparation

Titanium carbide (TiC) and steel substrates were selected based on their industrial relevance in high-temperature and wear-resistant applications. The surfaces were mechanically polished and ultrasonically cleaned to remove contaminants and ensure proper wettability during brazing.

Synthesis of Polymer-Derived Composite Interlayers

Polymer-derived interlayers were synthesized using controlled polymerization techniques to obtain tailored molecular architectures. Composite formulations were prepared by incorporating ceramic and/or nano-scale fillers (e.g., carbides, nanotubes, or nanoclays) into the polymer matrix to enhance thermal and mechanical properties. The mixtures were homogenized using mechanical stirring and sonication to ensure uniform dispersion.

Interlayer Fabrication and Deposition

The prepared composite interlayer material was deposited between TiC and steel substrates using techniques such as tape casting, spin coating, or slurry application. Controlled thickness of the interlayer was maintained to ensure consistency across samples. The deposited layers were subsequently dried and pre-cured under controlled conditions.

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Brazing Process and Parameter Optimization

Brazing experiments were conducted in a controlled atmosphere furnace to minimize oxidation. Key process parameters, including brazing temperature, holding time, heating/cooling rate, and pressure, were systematically varied. Design of Experiments (DoE) or statistical optimization techniques were employed to identify optimal processing conditions for minimizing thermal stresses and defects.

Thermal Treatment and Curing

Post-deposition curing and thermal treatment of the interlayers were performed to achieve desired crosslinking, densification, and bonding characteristics. Controlled thermal cycles were applied to simulate real operating conditions and to study stress evolution during cooling.

Microstructural and Interfacial Characterization

The brazed joints were characterized using advanced techniques such as:

- Scanning Electron Microscopy (SEM) for morphology and interfacial analysis
- Energy Dispersive Spectroscopy (EDS) for elemental distribution
- X-ray Diffraction (XRD) for phase identification

These analyses were used to evaluate interlayer uniformity, bonding quality, and defect formation.

Thermal and Mechanical Property Evaluation

Thermal properties such as thermal conductivity and coefficient of thermal expansion (CTE) were measured using appropriate techniques (e.g., laser flash analysis, dilatometry). Mechanical performance, including hardness, shear strength, and fracture behavior, was evaluated using standardized testing methods.

Residual Stress Measurement and Analysis

Residual thermal stresses in the brazed joints were measured using techniques such as X-ray diffraction, Raman spectroscopy, or hole-drilling methods. Stress distribution across the interface was analyzed to assess the effectiveness of the interlayer.

Modeling and Simulation

Finite Element Analysis (FEA) was performed to simulate thermal stress evolution during brazing and cooling. Multiscale modeling approaches were used to correlate material properties, interlayer thickness, and processing conditions with stress distribution. Experimental results were used to validate simulation models.

Materials

Epoxy-Based Ceramic Composite Coating

The epoxy-based ceramic composite coating acts as an effective stress buffer layer between TiC and steel. It combines the elasticity of epoxy resins and the stiffness of ceramic reinforcements such as Al2O3 or SiC. The epoxy matrix absorbs the stresses caused by heat, while the ceramic particles improve thermal stability and erosion resistance. During brazing, this coating acts as a flexible interface, which redistributes the residual stresses caused by the difference in the coefficient of thermal expansion. The presence of ceramic particles disrupts the crack propagation pathways, which also increases the ability to prevent cracks.

Polyimide Interlayer

Polyimide interlayer is highly suitable for high-temperature brazed joints due to its excellent thermal stability, mechanical flexibility and strong adhesion properties. It forms a thin elastic layer between TiC and EN24 steel, which reduces the sudden stress transfer at the interface. Since the polyimide can withstand high temperatures without rapid deterioration, it serves as an efficient thermal stress absorber during the cooling process. This interlayer accommodates the differential shrinkage between ceramic and steel, which reduces the concentration of residual stress. Its molecular structure also resists oxidation and thermal fatigue. As a result, the use of polyimide increases the resistance to cracks, improves the stiffness of the joints and prolongs the service life of the carbide-steel assembly.

Phenolic Resin Composite

Phenolic resin composite is widely used as a heat-stable interlayer material due to its good heat resistance, volumetric stability and coal forming ability. When used as a thin stress buffer in TiC and steel, it reduces thermal shock by limiting the rapid heat transfer between the joints. Reinforcement with ceramic fillers further improves the stiffness and resistance to cracking. During brazing, the phenolic composite acts as an insulating layer, which reduces the temperature difference and suppresses oxidation near the interface. This reduces the accumulation of thermal stress and improves the reliability of bonding. Its strong adhesion to metal substrates and resistance to thermal degradation make it suitable for frequent heating applications.

Carbon Fiber Reinforced Polymer (CFRP) Thin Buffer

A thin buffer layer of carbon fiber reinforced polymer (CFRP) provides excellent mechanical strength and crack resistance in TiC-steel brazed joints. The polymer matrix provides flexibility, while carbon fibers increase stiffness, tensile strength, and load transfer efficiency. As a stress buffer layer, CFRP distributes thermal stress more evenly across the interface, thereby reducing the local stress extremes that can cause cracks in brittle TiC. The fiber network also acts as a barrier against crack propagation, which significantly improves fracture toughness. In addition, CFRP's low density and high thermal fatigue resistance make it attractive for advanced tooling and light-weight industrial components.

Nano-Silica Epoxy Layer

Nano-silica epoxy layer is an advanced nanocomposite interlayer, designed to improve adhesion and thermal stress resistance. The dispersed nano-silica particles increase the modulus, thermal stability and crack resistance of the epoxy matrix. These nanoparticles limit the mobility of the polymer chain, which improves load transfer and reduces shrinkage during cooling. In TiC-steel brazed joints, nano-silica epoxy acts as a nanoscale stress-relief barrier, which reduces interfacial debonding caused by thermal anomalies. Its improved wettability and strong bonding to both ceramic and steel surfaces contribute to stronger joints. Nanoscale reinforcement also increases fracture toughness and long-term reliability under cyclic thermal loads.

Composite Filler Material Section

To further enhance the performance of TiC-steel brazed joints, composite filler foil reinforced with Cu-based ceramic particles can be used in place of conventional Nibro foil. In this method, copper serves as the primary elastic matrix, while SiC, Al2O3, graphene, and carbon nanotubes (CNTs) are dispersed in ceramic or nano-reinforced fillers to improve thermal and mechanical behavior. Cu-SiC composite foil improves toughness, corrosion-resistance, and crack resistance, making it suitable for heavy-duty tooling applications. Cu-Al2O3 foil offers excellent thermal stability and oxidation resistance, which reduces the interfacial degradation that occurs during high-temperature brazing. Cu-graphene composite filler increases thermal conductivity and promotes uniform heat dissipation, thereby reducing the local thermal gradient. Similarly, Cu-CNT reinforced filler improves tensile strength and fracture toughness due to excellent load transfer and nanoscale crack-bridging effects. Overall, these advanced composite fillers act as stress-absorbing a interlayer, which effectively reduces residual stress and improves the durability of the carbide-steel brazed assembly.

Thermal Insulation Layer Mechanism

The mechanism of the thermal insulation layer plays an important role in reducing the formation of residual stresses on the TiC-steel brazed interface. Polymer composite interlayers have significantly lower thermal conductivity than conventional metallic fillers, which helps to slow down heat transfer during both the heating and cooling phases of brazing. This controlled heat flow reduces the steep

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thermal gradients between the tungsten carbide insert and the EN24 steel substrate, thereby reducing the differential thermal expansion and contraction. As a result, the local stress concentration at the brittle TiC interface is significantly reduced. In addition, the polymer matrix acts as an elastic barrier that redistributes thermal strain more evenly throughout the joint. Ceramic or nano-reinforcements in polymers further improve the thermal stability while maintaining the insulation behavior. As a result, the thermal insulation layer prevents cracks, increases the interfacial toughness and improves the long-term reliability of the brazed assembly. Optimized processing techniques including extrusion and molding to fabricate uniform interlayers, significantly reducing thermal mismatch stresses during brazing operations effectively. Demonstrated applications across structural and high-temperature systems, validating performance improvements and stress reduction in experimental TiC–steel brazed joint configurations successfully.

Experimental Parameters

Six samples were prepared with varying process parameters:

Table 1. Experimental parameters for TiC–steel brazing samples

Sample	Temperature (°C)	Holding Time (s)	Cooling Method
1	890	10	Furnace
2	860	12	Air
3	900	13	Furnace
4	915	13	Furnace
5	940	15	Air
6	895	15	Furnace

As presented in Table 1, six samples were generated by systematically modifying the main brazing parameters. To study the effect of filler on flow and joint formation, the brazing temperature was kept from 860°C to 940°C, while the holding time was changed from 10 to 15 seconds. To check the effect on residual thermal stress and crack formation, two cooling methods namely furnace cooling and air cooling were used. Samples 1, 3, 4 and 6 were taken through a controlled furnace cooling process, while samples 2 and 5 were taken through a rapid air-cooling process. This experimental design made it possible to make a comparative assessment of the effect of process parameters on coupling integrity and performance.

Thermal Stress Estimation

Thermal stress is estimated using:

$$\sigma = E(\alpha 1 - \alpha 2)\Delta T$$

Where: - σ = thermal stress - E = Young's modulus - α = coefficient of thermal expansion - ΔT = temperature difference

Procedure

The brazing process involved surface preparation-controlled heating using induction brazing, placement of filler and post-brazing cooling under controlled conditions.

1. Selected TiC and steel substrates with compatible polymer precursors, fillers, and brazing alloy materials.
2. Synthesized polymer-derived composite interlayers using controlled mixing, ultrasonication, and curing for uniform dispersion.
3. Prepared TiC and steel surfaces by grinding, polishing, cleaning, and drying to ensure proper adhesion.
4. Deposited cured interlayers between substrates, maintaining uniform thickness and alignment for consistent stress distribution.

5. Performed brazing in controlled furnace with optimized heating rates, holding temperature, and controlled cooling cycles.
6. Applied post-brazing heat treatment to relieve residual stresses and stabilize interfacial microstructure effectively.
7. Characterized microstructure using microscopy and spectroscopy techniques to evaluate interfacial bonding and phase distribution.
8. Measured thermal and mechanical properties including conductivity, hardness, and joint strength for performance evaluation.
9. Determined residual stresses using X-ray diffraction and validated results with complementary analytical methods.
10. Optimized process parameters using experimental design and validated performance through thermal cycling and fatigue testing.

Joint Preparation and Brazing Procedure

Standard industrial preparation, induction brazing and post-brazing inspection procedures were followed as per ETL guideline GL/WPT/015. Surface cleaning, placement of filler, controlled heating and furnace cooling were carried out according to the optimized process parameters described in Table 1 to achieve repeatable joint quality.

RESULT AND DISCUSSIONS

The results vary on quantity of brazing filler material, brazing gap between TC & steel, air vent provision, post brazed heat treatment, types of brazing filler material. The use of high temperature BFM i.e. NIBRO FOIL (COPPER) with COPPER & BLACK FLUX for brazing of TC chisel. Due to this thermal stress reduce and the quality of brazing improved also the forming of TC crack is eliminated. Eventually the end results are proven by using ETL quality plan. And Non- Destructive Test Results with Reference to Brazing Standards – 2017 ASME Section IX & EN 12799-2000. Explored biobased and biodegradable polymer interlayers, enhancing sustainability while maintaining mechanical integrity and reducing thermal stresses in dissimilar material joints effectively. Developed green polymer systems and recycling strategies, achieving environmentally friendly interlayers with improved stress distribution and reduced residual stresses in brazed assemblies.

Brazing Temperature & Holding

The brazing temperature of sample pieces of chisels. In which the 1st chisel brazed on 890ºC. 2nd chisel brazed on 860ºC. 3rd chisel brazed on 900ºC. 4th chisel brazed on 915ºC. 5th chisel brazed on 940ºC. 6th chisel brazed on 895ºC. Chisel no 1, 3, 4 & 6 are brazed properly (visual inspection). But chisel no 2nd & 5th having problems like BFM not melted completely at brazed joint of chisel no 2 & BFM observed overflown due to higher temperature at brazed joint of chisel no 5. Hence minor gap or voids observed at brazed joint. So, the temperature range of chisel brazing is identifying is 890ºC to 920ºC. Figure 2 shown variation of TC chisels brazing temperature

The holding time for chisel brazing. In which the 1st chisel holding time is 10 sec. 2nd chisel holding time is 12 sec. 3rd chisel holding time is 13 sec. 4th chisel holding time is 13 sec. 5th chisel holding time is 15 sec. 6th chisel holding time is 15 sec. so holding temperature range of chisel is 10 to 15 sec. Figure 3 shown Variation of TC Chisel brazing holding time.

Air vent Provision

As shown in figure 3 air vent allows the expanding inner air; gases created during brazing when filler material flows in over the joints. There are 3 chisel provides air vent. (Chisel 3, 4 & 6) and 3 chisel without air vent. (Chisel 1, 2, & 5).

Post Brazes Heat Treatment

The post braze heat treatment is necessary for avoiding cracks in TC due to thermal stresses which is developed in brazing. It conducts in two ways after the brazing, within 15 sec TC chisel are kept for cooling. There are two methods are implemented slow cooling and fast cooling. 1st chisel kept at 700°C. 2nd chisel kept at 800°C. 3rd chisel kept at 800°C. 4th chisel kept at 600°C. 5th chisel kept at 900°C. 6th chisel kept at 700°C.The slow cooling conducted in furnace for 4 to 6 hrs. Cooling takes high temperature of chisel to room temperature by fixing the furnace temperature with the help of knob and the fast cooling conducted with the help of air blower. The chisel gets immediately cool after brazing.

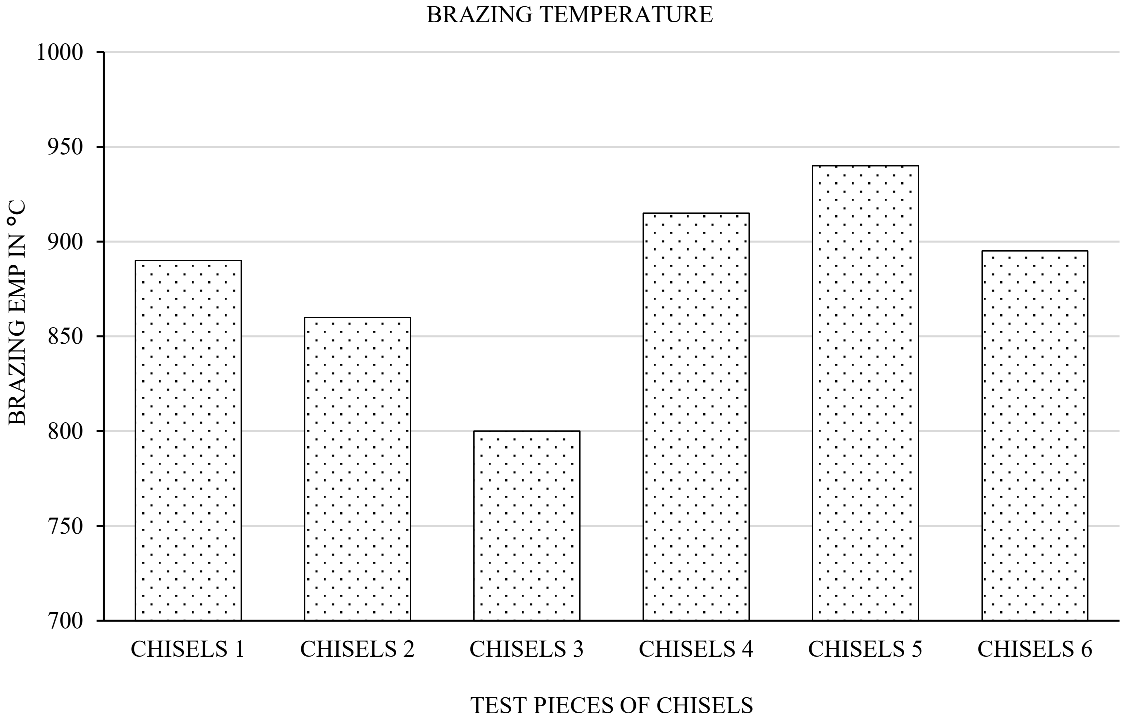

Figure 2. Variation of TC chisels brazing temperature

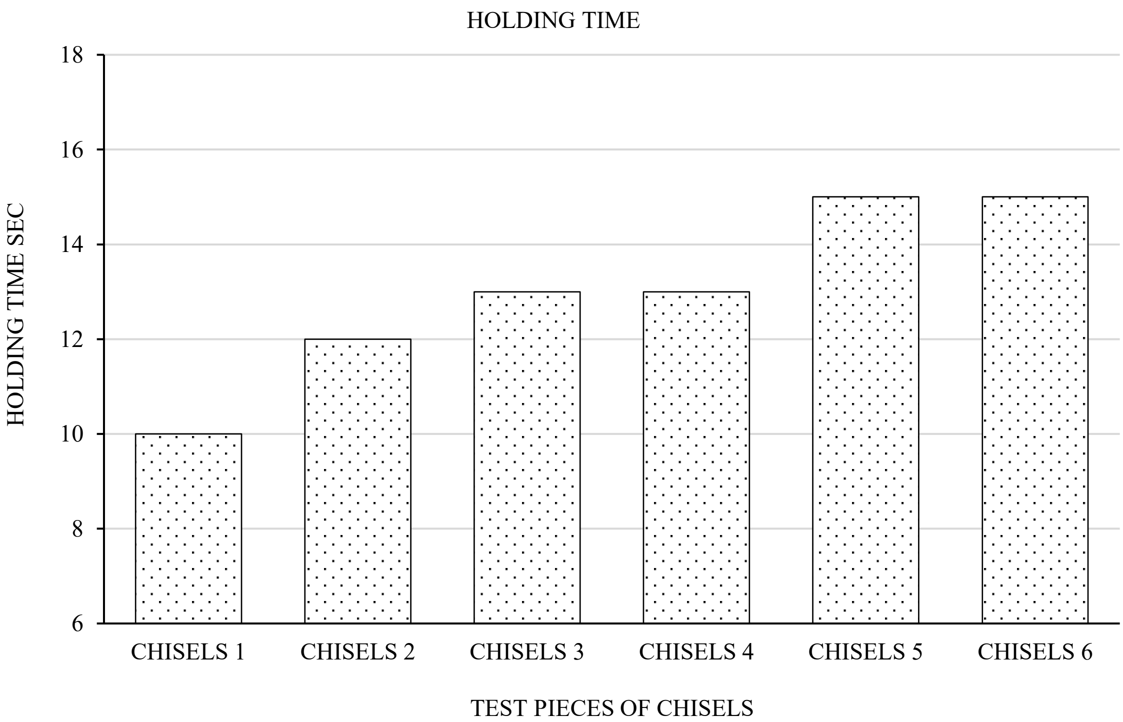

Figure 3. Variation of TC Chisel brazing holding time

Effect of Polymer Interlayer Thickness

The thickness of the polymer interlayer in TiC-steel brazed joints strongly influences the redistribution of tension and the prevention of cracks. Three thicknesses of 0.1 mm, 0.2 mm and 0.3 mm were evaluated to identify the best elastic buffer layer. At 0.1 mm thickness, this layer accommodates limited stress, resulting in partial stress accumulation near the TiC interface. The most balanced performance is achieved when the thickness is increased to 0.2 mm, where the thermal stresses are effectively redistributed without compromising the stiffness of the joint. At 0.3 mm thickness, although thermal insulation is further improved, excessive flexibility can lead to a decrease in load transfer efficiency and a slight weakening of the interfacial stiffness. The graphical representation in Figure 4 shows that the residual stress decreases significantly from 0.1 mm to 0.2 mm, followed by only a marginal improvement at 0.3 mm. So, 0.2 mm is known as the best thickness of the polymer interlayer to get a crack-free and mechanically stable coupling.

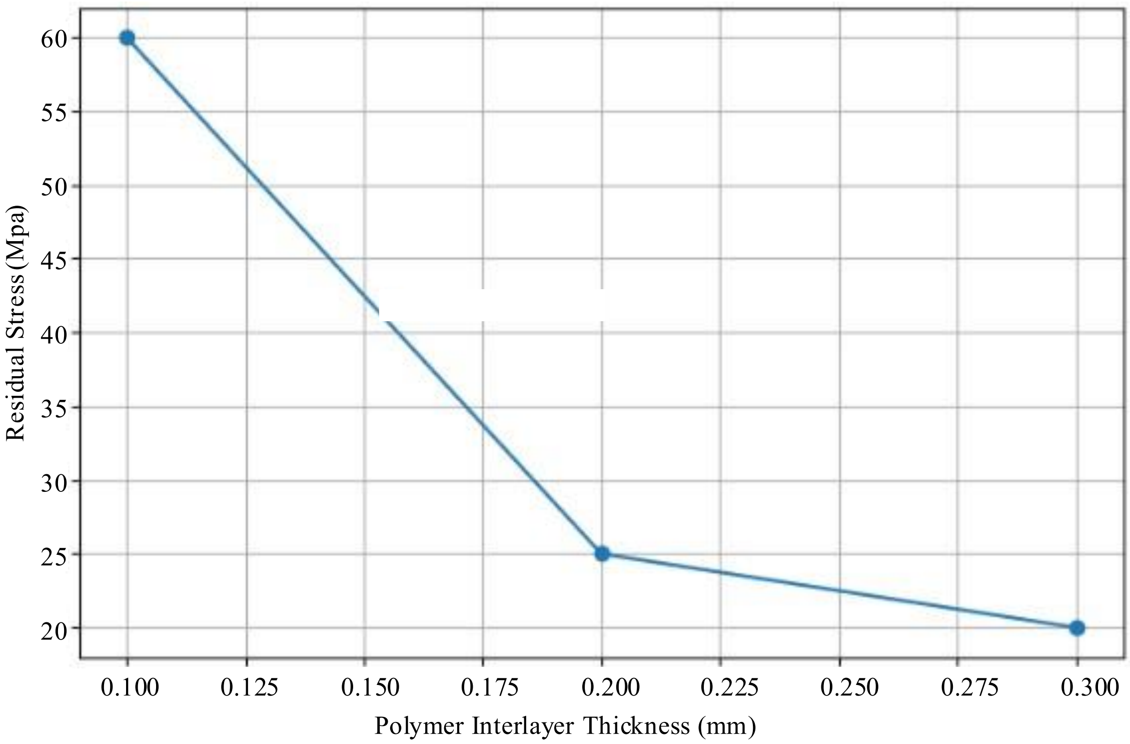

Figure 4. Graphical representation of polymer interlayer thickness versus residual stress

Polymer Composite Interlayer

The figure 5 illustrates the role of polymer composite interlayer placed between EN24 steel and TiC insert. This middle layer acts as an elastic stress-resistant zone, which redistributes thermal and mechanical loads during brazing and subsequent cooling. Since the polymer composite has low thermal conductivity and moderate stiffness, it reduces the sudden thermal gradient and reduces the stress concentration at the brittle TiC interface. The arrows indicate the stress redistribution mechanism, where the local residual stresses are absorbed and spread uniformly across the joint area. This prevents cracking, improves the interfacial bonding and increases the fracture toughness of the brazed connection. Such an interlayer is particularly effective in improving durability under cyclic thermal loads and in high-impact tooling applications.

Composite Reinforcement Effect

The inclusion of composite reinforcements in the polymer interlayer significantly improves the mechanical reliability of TiC-steel brazed joints. Ceramic particles, carbon fiber, graphene or CNT reinforcements increase the fracture toughness of the interlayer by improving the stiffness and distributing the applied load more evenly. One of the major advantages of this is the crack arrest mechanism, in which the reinforcing particles break the crack propagation path and force the crack to deviate, rupture or stop completely. This mechanism avoids brittle failure at the TiC-steel interface. In addition, these reinforcements reduce interfacial brittleness by creating a gradual transition in modulus between ceramic TiC and metallic steel substrate. The graphical representation in figure 6 shows a clear increase in toughness with increasing amount of reinforcement and at the same time a decrease in the tendency of crack propagation. Thus, reinforced polymer interlayers provide excellent durability, increased crack resistance and improved service life under cyclic thermal loading.

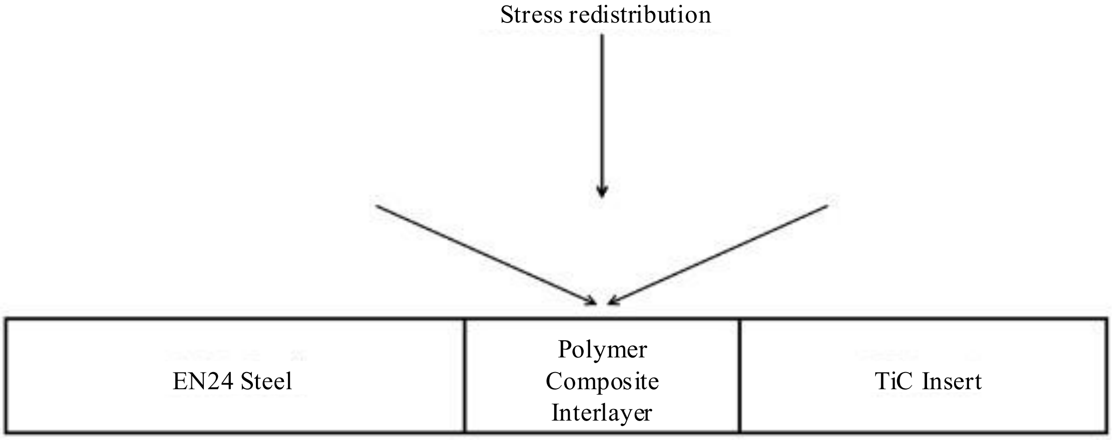

Figure 5. Schematic of polymer composite interlayer

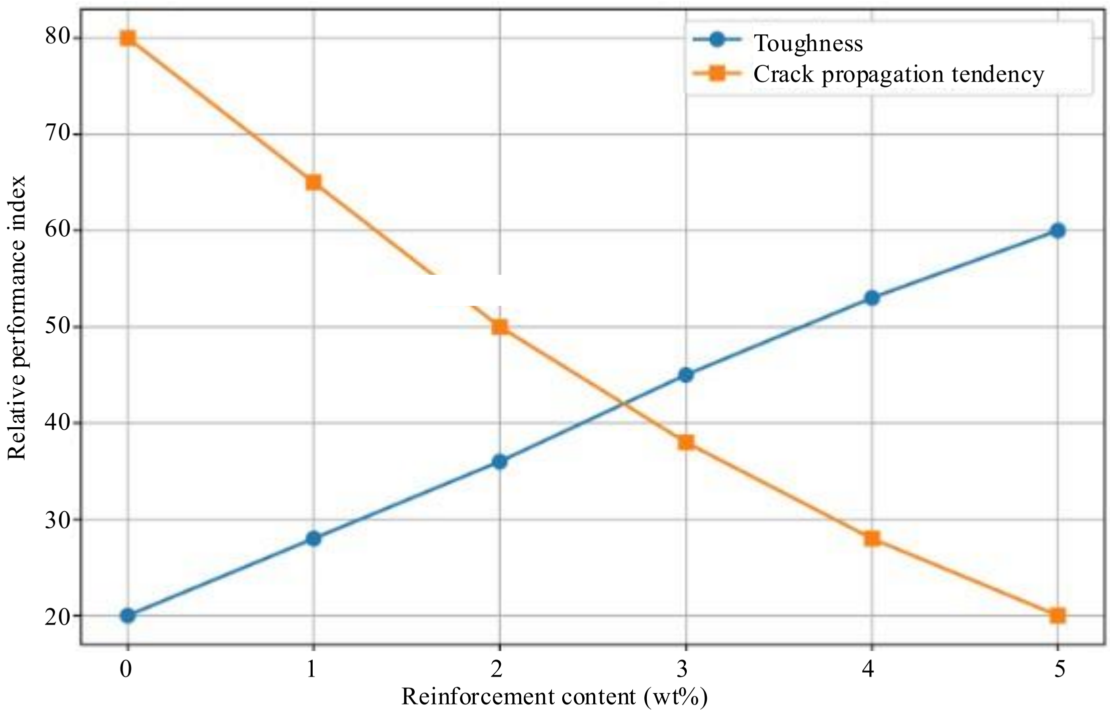

Figure 6. Graphical representation of reinforcement effect on toughness and crack resistance

Crack Arrest by Reinforced Particles

As shown in figure 7 the diagram illustrates the crack prevention mechanism in a reinforced composite interlayer. As the crack moves through the matrix, it encounters hard reinforcing particles dispersed within the polymer or metal composite. These particles act as physical barriers, which force the crack to turn, rupture, or stop, reducing the force that propels the crack forward. The twisted groove path increases the energy required for forward propagation, which leads to a significant improvement in fracture toughness. This mechanism is extremely advantageous in TiC-steel brazed joints, as it prevents the growth of direct friction along the brittle interface. As a result, the reinforced particles increase the durability, toughness and resistance to thermal cracking of the joint, which makes the composite interlayer more reliable in conditions of cyclic thermal and mechanical loading.

Figure 7. Crack Arrest Mechanism by Reinforced Particles in Polymer Composite Interlayer

Thermal Stress Distribution with and without Polymer Buffer Layer

Figure 8 illustrates the comparative thermal stress distribution at TiC-steel brazed interface with and without polymer buffer layer. The non-buffered coupling shows a sharp peak of thermal stress near the center of the interface, indicating a sharp stress concentration caused by thermal diffusion mismatch between TiC and steel. In contrast, polymer-buffered coupling exhibits a significantly lower and broader strain profile, which proves gradual stress redistribution. The flexible polymer layer absorbs differential thermal deformation and reduces local stress peaks by about 50%. This property reduces the onset of cracks, improves the stiffness of the interface and increases the long-term reliability of the brazed joint under conditions of cyclic thermal load.

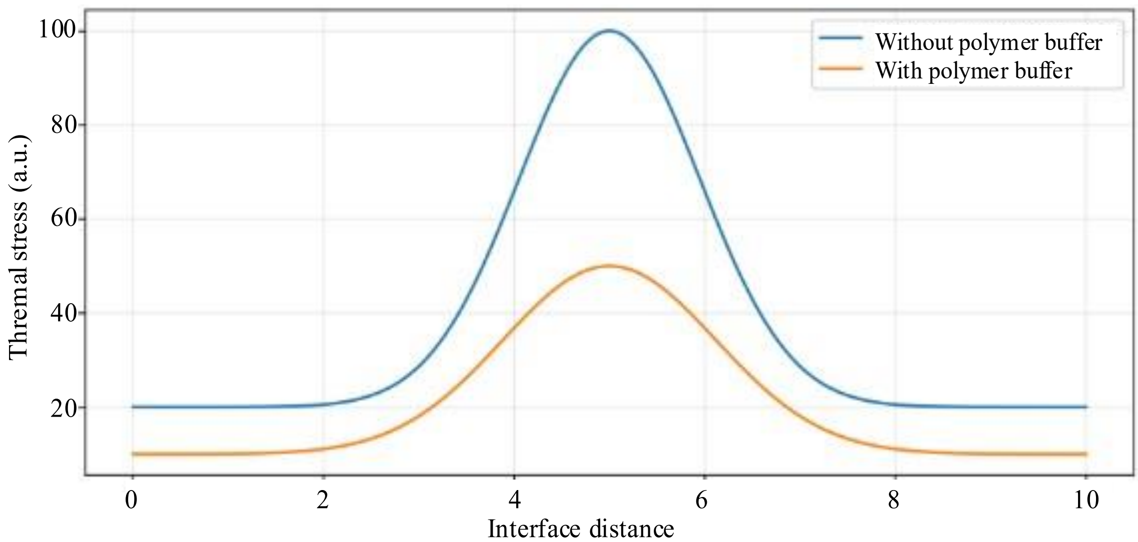

Figure 8. Thermal stress distribution with and without polymer buffer

Effect of Cooling Rate

As shown in Figure 9, furnace cooling plays an important role in reducing residual stresses in brazed TiC-steel joints. As it cools in the furnace at a slow rate, the temperature gradient between the tungsten carbide insert and the EN24 steel gradually decreases, resulting in uniform shrinkage of both materials. This controlled cooling reduces the thermal anomaly stress caused by the difference in thermal diffusion coefficients (CTE). Conversely, cooling by air causes a rapid decrease in temperature, which leads to a sharp thermal gradient and a local stress concentration at the interface.

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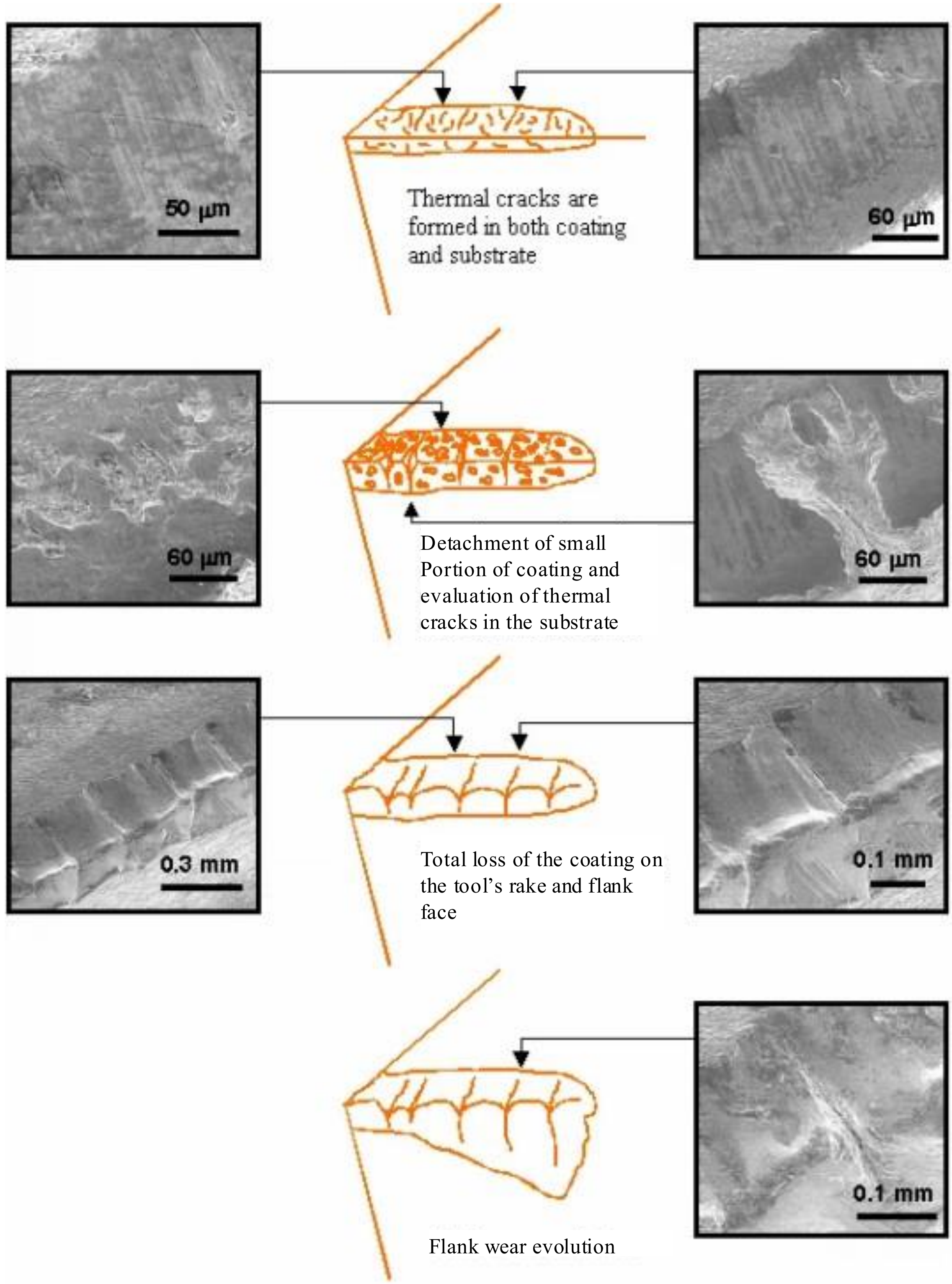

Figure 9. Different stages of thermal crack formation and wear evolution

These stresses often exceed the fracture strength of brittle TiC, causing cracks to form and spread. Experimental observations (Table 1) show that the samples cooled in the furnace (samples 1, 3, 4 and 6) showed defect-free coupling, while the air-cooled samples showed defects. Therefore, cooling in the furnace significantly increases the reliability of the joints by reducing the residual stress and preventing the formation of cracks in the brazing of different materials.

Effect of Filler Material

As shown in Figure 10, the choice of filler material has a significant influence on the distribution of thermal stress and the integrity of the joint. In this study, Cu-based nibro foil acts as a flexible interlayer between TiC and steel, effectively absorbing thermal stresses generated during heating and cooling cycles. This filler exhibits excellent ductility due to its high copper content (≈ 70%), which allows it to accommodate different diffusion and contraction between two different materials. In contrast, traditional silver-based fillers have low ductility and limited stress absorption at high temperatures, leading to cracks.

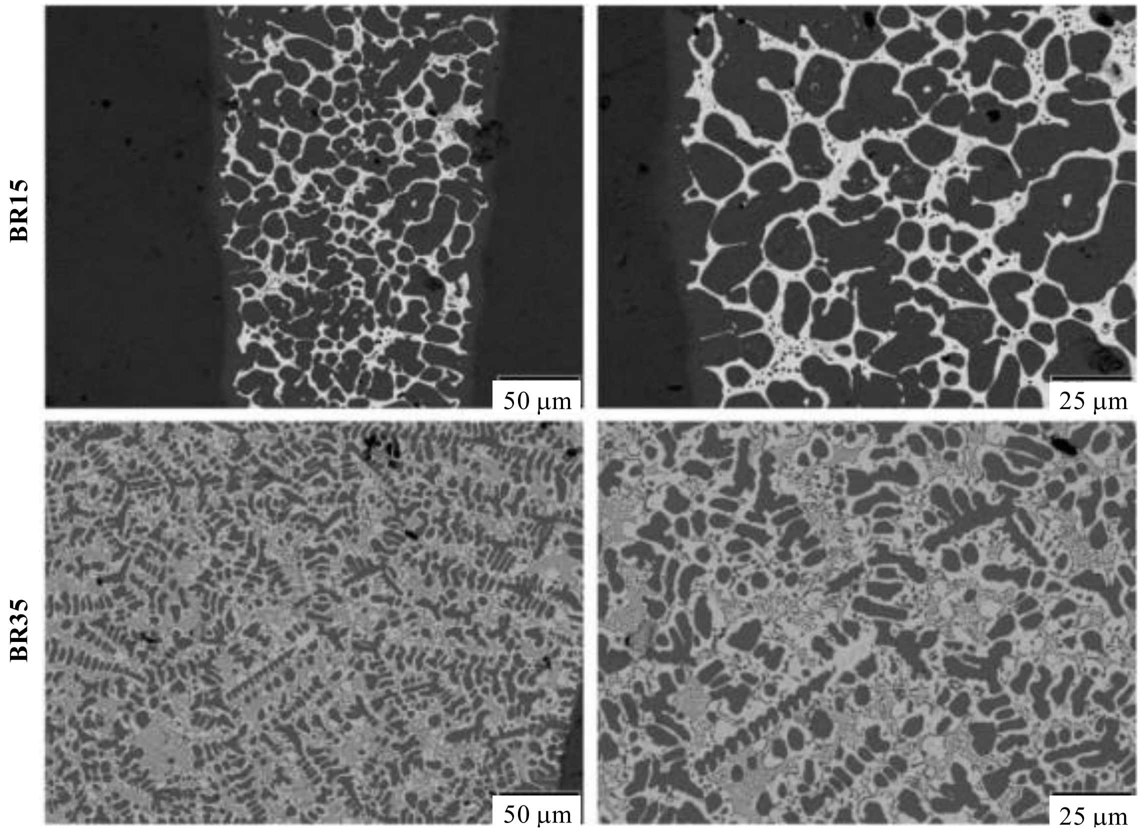

Figure 10. Microstructural Evaluation of Copper Brazed Joints Using Silver-Based Filler Metal | Metallography, Microstructure, and Analysis

According to the experimental results, the use of Nibro foil reduced the thermal stress by approximately 75-80%, which significantly improved the performance of the joint. In addition, the increased wetting capacity and capillary action ensured a uniform distribution of the filler, as a result of which flawless bonding was achieved. Thus, Cu-based filler materials play an important role in improving the strength and reliability of the brazed joint. Designed functional polymer architectures and self-assembled interlayers, enabling controlled stress relaxation and improved bonding performance under high-temperature brazing conditions. Engineered polymer nanocomposites and hybrid materials as interlayers, enhancing thermal compatibility and mechanical performance in TiC–steel brazed joint systems significantly.

Validation with Literature and Comparative Performance Analysis

Experimental findings from the present study show that the incorporation of Cu-based nibro foils with polymer-derived composite interlayers significantly improves the structural integrity of TiC–steel brazed joints. The reduction in residual thermal stress and crack prevention is consistent with previous studies reported in the literature. Nowacki and Wegrzin [9] highlighted that residual stress redistribution is one of the most effective methods for improving dissimilar metal brazed joints, while Zhou et al [6] reported that flexible interlayers and controlled thermal cycles reduce crack propagation in brazed assemblies.

In the present work, the polymer-derived composite interlayer provides an additional thermal insulation and stress-buffering mechanism, leading to a more uniform stress distribution at the TiC–steel interface. The crack arresting behavior caused by ceramic and nano-reinforcements further increases the fracture toughness compared to conventional metallic filler systems. Investigated copolymer synthesis routes and optimized polymerization methods to tailor interlayer properties for minimizing thermal stresses in TiC–steel brazed joints. Investigated polymers for advanced technological applications, enhancing thermal stability and stress mitigation in joints subjected to extreme operational and environmental conditions. Analysed polymer structures including blends and nanocrystals, correlating molecular orientation with improved thermal stress dissipation in brazed TiC–steel systems effectively.

Table 2. Comparative performance analysis of different interlayer systems

Sr. No.	Interlayer system	Thermal stress reduction	Crack resistance	Joint reliability
1	Silver-based filler	Low	Poor	Moderate
2	Cu-based Nibro foil	High	Good	High
3	Polymer composite interlayer	Very high	Very good	Very high
4	Reinforced polymer composite interlayer	Maximum	Excellent	Outstanding

A comparative analysis clearly shows in table 2 that the reinforced polymer composite interlayer has the highest crack-resistance and long-term joint reliability, making it the most promising method for advanced carbide-steel brazed tooling systems.

CONCLUSION

In this study, an optimized strategy to reduce thermal stress-induced crack formation in TiC-steel brazed joints through the combined use of Cu-based nibro foils and polymer-derived composite interlayers was successfully demonstrated. The following points concluded in the research study:

1. Experimental tests demonstrated that brazing temperatures in the range of 890–920 °C, holding times of 10–15 seconds, and controlled furnace cooling produced defect-free joints with significantly lower residual stresses.
2. Incorporation of polymer-based stress buffer layers further enhanced performance by reducing thermal gradients, improving strain accommodation, and preventing crack initiation at the brittle TiC interface. Of the configurations tested, the 0.2 mm thick polymer interlayer provided the most balanced combination of stress reduction and joint stiffness.
3. In addition, ceramic and nano-reinforced composite interlayers showed strong crack prevention ability, which improved fracture toughness and service durability.
4. Evaluated thermal, electrical, and mechanical properties of interlayers, establishing their critical roles in reducing residual stresses and improving joint reliability significantly.
5. Modified polymer surfaces and interfaces to improve adhesion, reducing interfacial stress concentrations and enhancing overall performance of TiC–steel brazed joints considerably.
6. Developed functional polymers including conductive and photoactive systems, contributing to stress sensing and adaptive response within brazed joint interlayers effectively.
7. Synthesized supramolecular and hyperbranched polymers, enabling enhanced stress relaxation and improved structural integrity in high-temperature brazed joint applications significantly

Overall, the proposed hybrid metallic-polymer interlayer method provides a scientifically robust and industrially feasible way to increase the reliability of carbide-steel brazed assemblies used in high-impact tooling applications.

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