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A Study of Recent Developments in Amorphous Brazing Foils

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ABSTRACT: In recent years, efforts have been made to address the shortcomings of conventional brazing foils stemming from solidification processes through optimization of production parameters and the addition of filler metals. Amorphous brazing foils with low melting points, rapid solidification, and the addition of filler metals are being produced. This study aims to review previous work in this field and investigate the spectrographic properties of joints made with amorphous brazing foils. Within the scope of this study, dissimilar duplex stainless steel and medium carbon AISI 4140 steel were joined using MBF-1 metallic foil using the vacuum diffusion bonding technique, which boasts several properties such as exceptional processing accuracy and suitability for large-scale production. Microstructure and EDS analyses demonstrated that the joint produced was mechanically and metallurgically well bonded.

KEYWORDS: Amorphous foil, Diffusion welding, Brazing, MBF-51, Microstructure

INTRODUCTION

The rapid development of manufacturing technologies is constantly increasing the need for smaller, more reliable, and higher-performance components. Consequently, brazing processes are also undergoing significant transformation. Brazing is a technique for joining materials based on the diffusion of elements between the brazing and the base material [1].

Amorphous brazing foils, which have been significantly developed in recent years alongside traditional brazing alloys, are a type of eutectic amorphous metal that acts as a "filler metal" between two metal parts during brazing processes by melting and cooling them, facilitating metallurgical bonding. They are particularly popular in many structural applications, including aerospace, healthcare, high-density packaging, thermal management, precision automotive, high-temperature connections, and electronics [2, 3].

Amorphous brazing foils are produced by blending metalloids such as silicon, boron, and phosphorus with transition metals such as nickel, iron, and copper, then cooling the liquid alloy rapidly enough to prevent crystalline formation. Careful control of the metalloid concentration during this rapid solidification process allows the eutectoid point to be reached. This ensures a ductile, effective bond and a strong, flawless joint [3].

Amorphous brazing foils are produced using high-speed solidification techniques such as melt-spinning. This prevents the crystalline nucleation process, resulting in a glassy structure [4]. Disorder at the atomic level, or an amorphous structure, refers to the absence of grain boundaries. This structure can positively influence fatigue and cracking behavior. Because these structures are not crystalline, they form alloys with irregular atomic arrangements. Compared to traditional brazing fluxes or wires, these foils offer advantages such as higher mechanical strength, a more homogeneous microstructure, and limited intermetallic phase formation [3].

Amorphous foils generally contain metalloids such as boron (B), silicon (Si), and phosphorus (P) and can have low melting temperatures. Ni-Cr-Si-B-based amorphous foils provide high strength in terms of both mechanical strength and corrosion resistance [5].

In a study conducted by Bobzin et al., Fe-based amorphous foils were developed to reduce the use of Ni-based foils and reduce their cost and potential environmental damage. New amorphous foils with the Fe-Ni-Cr-Si-B system were developed as an alternative to traditional Ni-based foils. This five-element system demonstrated a successful amorphous structure and favorable flow properties [1].

A new amorphous brazing based on Ni-Cr-Si-B was developed for the GH4169 superalloy, which was optimized for high temperature joining and modified the Nickel-based alloy [6]. In other previous studies [7, 8], new Ni-Cr-Si-B filler metal (JNi-5) was designed by reducing the Si and B content and adding special alloying elements (Such as Co and Y). The elements B and Si are generally considered melting point depressants in the filler metal to lower brazing temperatures. However, excessive addition of these can produce large brittle boride and silicide phases, which can increase the likelihood of joint brittle fracture and seriously reduce reliability. Therefore, in another study [9], it was investigated that appropriately reducing the B and Si content in the filler could limit the formation of brittle compounds when joining GH4169 (Ni-based superalloy) alloy at lower temperatures. In GH4169 components, brazing joints were improved using a new Ni-Cr-Si-B-based amorphous filler, providing high-temperature strength and microstructural stability. Furthermore, the addition of Co and Y can be said to increase joint bond strength through solid-strengthening effects [10].

Adding an element that lowers the brazing temperature is a widely researched method for increasing bond strength. Adding Sn to Sn-doped amorphous foils in the Ti-Zr-Cu-Ni-Sn system lowered the melting temperature and improved mechanical performance [11]. Beryllium can form limited solid solutions and compounds with titanium, and small amounts of beryllium can lower its melting point. Other elements such as V, Cr, Fe, and Co may also have the same effect [12] . Brazing joints made with a Sn-containing Ti-Zr-Ni-Cu-Sn amorphous foil in joining Ti-6Al-4V (TC4) alloy offer significant potential for titanium applications, especially in aerospace and biomedical fields [13-15]. Another study found that using different fillers (e.g., amorphous Ti and Zr-based fillers) to join Ti-6Al-4V and 316L stainless steel affected the microstructure and mechanical properties [16]. Low-temperature brazing has become possible with Ti-Cu-Zr-Pd amorphous foils for joining titanium alloys such as Ti-6Al-4V. Vacuum brazing of Ti alloys typically uses filler metals alloyed with lower melting points, such as Ti-Cu alloys or Ti-Zr-Ni-Cu alloys [17]. A low melting point makes brazing easier, but it also reduces the high-temperature performance of the joints [18].

Thanks to recent research, amorphous foils can now be produced in flexible form. This flexible structure allows new Fe-based foil studies to increase their applicability to components with complex geometries [2]. In addition, more precise alloy design is made in brazing processes, thus improving control of intermetallic compound (IMC) formation [19]. In this context, a study by Xie et al. developed Ni-W-B amorphous brazing alloys with high W (tungsten) content. Adding W to this alloy increased the solubility of brittle phases (intermetallic compounds) and improved mechanical performance [20]. Similarly, a later study demonstrated the role of W addition in reducing brittle phases in Ni-based filler metals [21].

Wu et al. systematically investigated the effects of temperature and holding time on the microstructure and bond properties of brazing processes using Ti-Zr-Cu-Ni amorphous foils. This study demonstrated that interfacial microstructure and mechanical performance were improved with certain parameters [22]. Moreover, as the brazing temperature increases, the growth of interfacial Cu-Ti intermetallic compounds greatly deteriorates the shear strength of the joint [23]. In the brazing joint of titanium alloy made using Ti-15Cu-15Ni and Ti-15C-25Ni filler metals, fracture was observed along the Cu-Ni rich Ti phase [24]. Therefore, when the joint is subjected to uniaxial tensile loading, cracks form and cause premature joint failure in the brittle Cu-Ni rich Ti phases in the joint [25-27]

The production of amorphous foils often requires rapid solidification processes, which can lead to production problems. The inherent lack of crystalline slip planes in amorphous structures results in limited plastic deformation before failure, complicating both manufacturing processes and end-use applications where vibration or physical stress may occur. Amorphous structures are inherently prone to crystallization; therefore, process temperatures must be carefully selected and the amorphous structure maintained. Their widespread use is further limited because amorphous metals crystallize when heated above their crystallization temperature, often well below their melting point. These characteristic limits operating temperatures and processing options and is a particularly important criterion in applications such as power electronics, where thermal stability is crucial. Current production methods for high-quality amorphous metals require specialized equipment and precise process control, resulting in significantly higher material costs compared to traditional crystalline alternatives. This cost differential has primarily limited amorphous metals to premium applications, where their performance advantages clearly justify the price difference. Standardization issues further hinder their adoption by industry due to the relatively recent emergence of these materials; This is because comprehensive standards for testing, specification, and application design of these materials are not yet sufficiently developed compared to traditional materials. This regulatory gap creates uncertainty for design engineers and slows integration into established supply chains and manufacturing processes. Control of intermetallic compounds is still not fully optimized in some applications, so further development of alloy design and process parameters is necessary [28].

Despite these drawbacks, Ni-based foils are still common to achieve higher-performance connections in the future, although Fe-based alternatives are being widely investigated due to the cost of Nickel [29]. Alternative studies such as high W content are trying to control the formation of brittle intermetallic phases [20]. Studies on Fe-based amorphous foils and new high entropy alloys (multi-element) are increasing [30]. Efforts are underway to develop functional amorphous foils, excluding brazing, in terms of thermal management (heat distribution), magnetic properties, and electrical properties. Lower melting points and recyclable alloy designs in the production of amorphous foils can be seen as opportunities to make them more environmentally attractive.

This study was conducted to investigate the bonding mechanism occurring in the diffusion-bonded region of amorphous brazing foil using optical microscopy (OM) and scanning electron microscopy (SEM). Furthermore, elemental analysis of the bonded region was conducted using Energy Dispersive Spectrometry (EDS). This demonstrated the effective bonding properties of the MBF-51 amorphous brazing foil.

2. MATERIAL AND METHOD

In this study, duplex stainless steel and AISI 4140 carbon steel were joined using MBF-51 brazing foil using the diffusion welding technique. Samples were prepared with a diameter of 10 mm and a length of 100 mm as shown in Figure 1, and their surfaces were sanded with 120, 400, and 800 mesh abrasives, respectively. The diffusion welding process was performed by placing MFB-51 foil between two cylindrical surfaces according to the parameters given in Table 1.

Figure 1. Samples with a diameter of 10 mm and a size of 100 mm; a) Duplex stainless steel, b) AISI 4140 steel

Diffusion welding was performed on the diffusion bonding vacuum welding machine (Figure 2) available in the Metallurgical and Materials Engineering Department of Nevşehir Hacı Bektaş Veli University, Faculty of Engineering and Architecture.

Figure 2. Vacuum Diffusion Welding Machine

The samples were placed in a graphite cylinder enclosure within the furnace for oxidation resistance. Diffusion welding was performed under vacuum diffusion conditions with a 0.2 kN weight applied to the sample.

In the study, a duplex type of stainless steel, MBF-51 foil, ~40-50 µm thick, the specifications of which are given in Table 1, was used to bond all contacting surfaces to medium carbon AISI 4140 steel under 0.50 MPa pressure and within 30 minutes. The diffusion welding process was performed at a temperature very close to the melting temperature of the foil used. Thus, with the increased diffusion rate and lower pressure and time, micro voids at the interface of the two dissimilar steels disappeared, resulting in a robust joint.

Table 1. Diffusion bonding specifications

Interconnector metal (wt%)	Diffusion temperature (^{0}C)	Diffusion time (s)	Interconnector thickness (µm)	Interconnector melting point (^{0}C)
MBF-51 (70-80Ni-10-20Cr-5-10Si-1-5B- Co-1 max)	1000	1800	40-50	(1013 – 1126 °C)

For metallographic examination, the samples were first sanded with 120, 400, 800, and 1200 grit abrasives, and the surfaces were polished on a polishing cloth using a 3 µm diamond solution. Subsequently, the duplex stainless steel surface was electrolytically etched with a 40% NaOH solution, and the 4140-steel surface was chemically etched with a 3% Nital solution.

Microstructural analyses of the duplex stainless steel, 4340 steel, and MBF-51 nickel-based foil were performed using a Nikon MA 100 optical microscope and a Clemex image analysis system equipped with an EDX and an SEM (HITACHI SU5000).

3. FINDINGS AND DISCUSSION

In the optical microscope image of the connection of duplex stainless steel and AISI 4140 steel made by diffusion welding using MBF-51 foil, the microstructures of duplex stainless steel with ferrite and austenite structures and AISI 4140 steel consisting of mixtures of cemented carbide, martensite, retained austenite and ferrite are seen (Figure 3). It is clearly seen from the micrograph that MBF-51 foil provides good mechanical and metallurgical bonding, in agreement with previous studies [31].

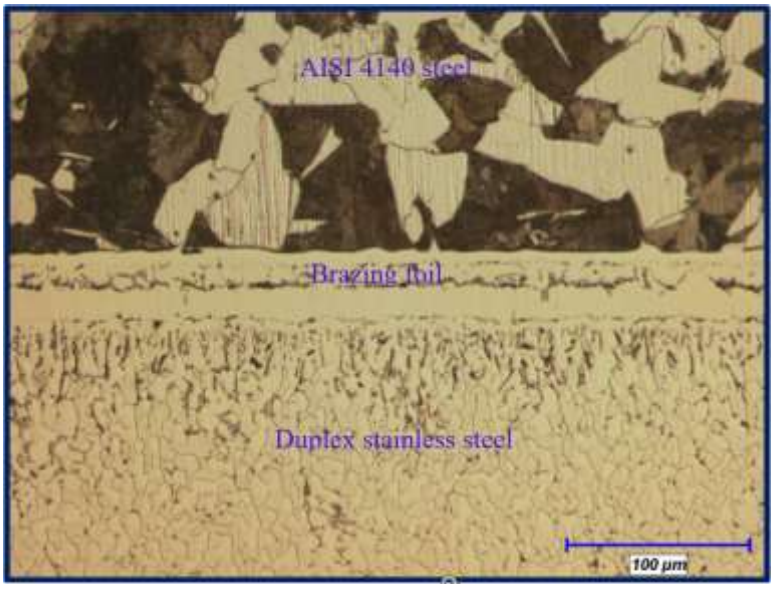

Figure 3. LM micrograph of steel samples bonded with MBF-51 brazing foil

SEM microstructure image and EDX analysis of the joint made with MBF-51 (Ni-Cr-B-Si) foil are given in Figure 4. Light elements such as B are not easy to identify in this research, but it is assumed that B diffuses into the joined steels and forms a solid solution of Ni, Fe and C in the interlayer structure as expressed in the previous study [31]. This means that Fe, Ni, C, Cr, Si, and high levels of chromium borides are formed at the grain boundaries of the bond layer. There is no penetration of B along the grain boundaries in the same steel samples, indicating that B is primarily contained within the hard-interlayer binder layer. This suggests that chromium boride phases remain along the interface of the steel samples and along the centerline of the hard-interlayer binder layer, where a strong presence of Cr is observed. NiSi intermetallic phases are present along the centerline of the hard-interlayer binder layer, which is surrounded by a solid Ni-Cr-B-Si solution.

The SEM image of diffusion bonding with MBF-51 foil, shown in Figure 4, indicates a lower Cr concentration in the Ni-rich interface region. The intermetallic phases within the braze layer are brittle and can cause crack propagation, as discussed in previous studies [32, 33].

Nickel and boron in the composition of the MBF-51 foil enhance bonding by diffusion. Eutectic boride and silicide phases are present in the bonding region, but as reported in a previous study [31], they do not have significant detrimental effects because they are encapsulated in a ductile matrix phase.

The bond interface clearly separates the regions formed by the crystallization of the filler metal (FM) and the bulk of the base metal (BM). The microstructure of the BM particles consists of three closely sequential morphological zones. The zone adjacent to the bond interface appears pearlitic, containing fine, narrow chromium boride grains formed within the original grains. The adjacent zone contains chromium borides as distinct, narrow, clustered particles at the BM grain boundaries. Boron is present in sufficient quantities to determine segregation at the twin boundaries, but not in sufficient amounts to cause the bulk of the grains to separate. This situation is considered to be due to the extremely low intergranular solubility of Boron in all high alloy materials, similar to the structure established in a previous study [34].

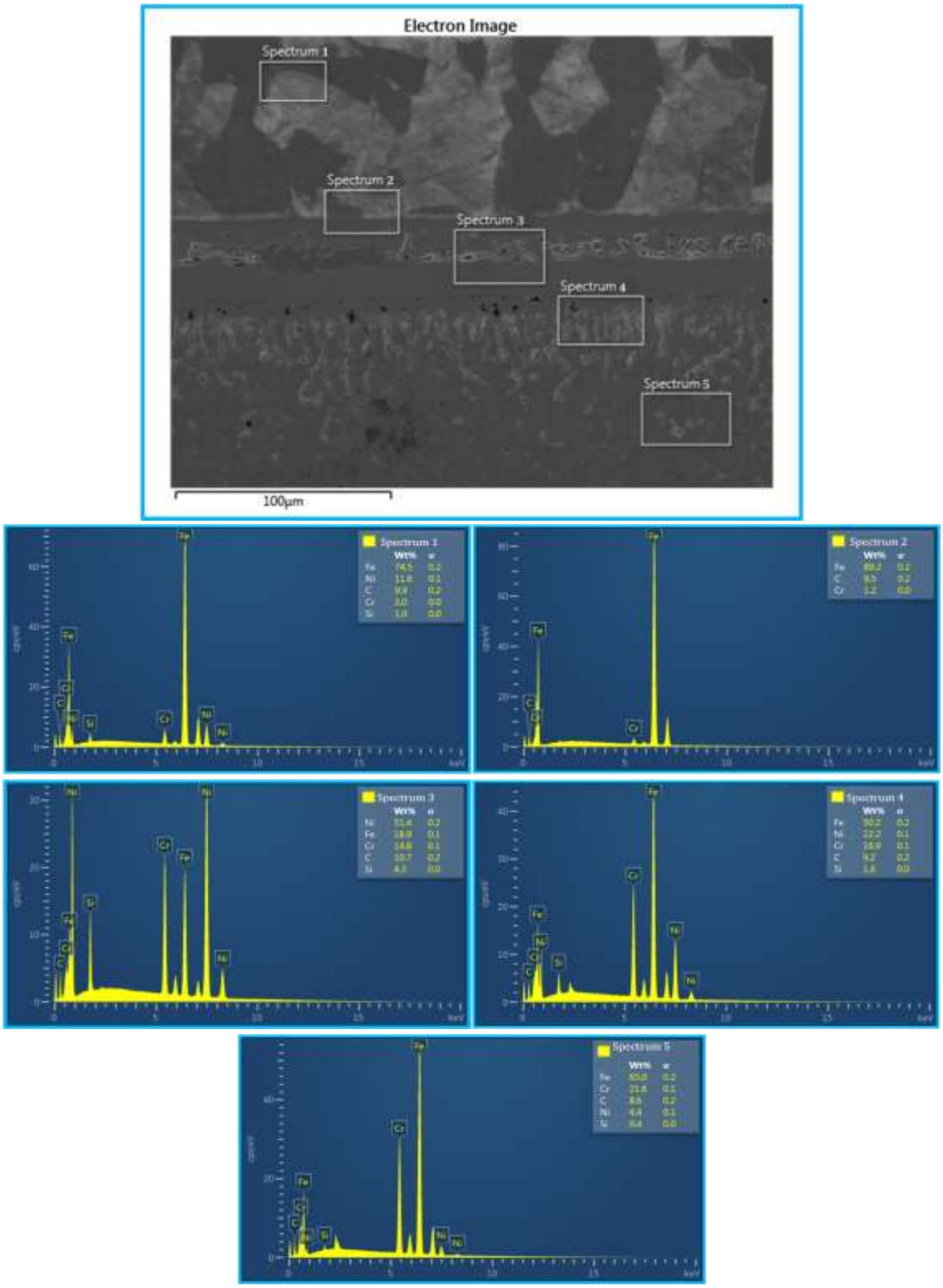

Figure 4. SEM micrographs and EDX analyses of duplex type stainless steel and AISI 4140 steel bonded with MBF-51 foil

The low sensitivity of the BM microstructure to the joint thickness is due to the characteristics of diffusion processes during the relatively short time of the diffusion cycle. At the beginning of the metallurgical interaction between liquid BM and solid BM, significant elemental concentration gradients are established across the interface for boron, silicon, iron, and nickel. At the same time, boron activity in BM is lower due to the influence of silicon. Therefore, boron has a high driving force to diffuse into AISI 4140 steel and form chromium borides at grain boundaries. As reported in previous work [35], the diffusion rate of Boron is twice as high as that of silicon and especially higher than that of nickel and iron. The diffusion mass transfer of other elements is quite small. Therefore, boron diffuses very rapidly and evenly across the interface into the solid stainless steel, reducing its concentration in the liquid FM and simultaneously forming chromium borides in AISI 4140 steel.

The micrograph shown in Figure 4 is of a joint between two dissimilar cylindrical specimens. The rounded shape of the plates, resulting from the difficulty of pressing perfectly flat surfaces in a very small area, produced gaps of variable width that increased in both directions from the central location. The gap dimensions are highly sensitive to the joint structure. These dimensions determine the thickness of the liquid FM that fills this gap due to capillary effects [31].

5. CONCLUSION

Amorphous brazing foils offer significant advantages over traditional brazing methods in terms of mechanical strength, microstructure control, and production benefits. Research in recent years has focused on the development of innovative alloys and flexible foils, particularly in Ni-Cr-Si-B and Fe-Ni-Cr-Si-B systems. However, challenges such as production scalability, the risk of crystallization, and the formation of intermetallic compounds remain at the heart of academic and industrial research. In the future, more sustainable, functional, and economical amorphous, brazing solutions will gain significant importance. In order to contribute to the applicability of recent developments in amorphous brazing foils, the diffusion welding technique of duplex stainless steel and AISI 4140 steel was combined using MBF-51 metallic foil. The following conclusions were drawn as a result of the study:

1. Structural problems may arise in the production of amorphous foils produced based on rapid solidification principles.
2. The absence of crystalline slip planes in amorphous structures can complicate end-use applications.
3. Because amorphous structures lack grain boundaries, they exhibit superior performance in terms of crack propagation and fatigue resistance. In this regard, element optimizations that reduce brittleness in newly developed alloys are attracting attention.
4. Crystallization should be prevented by amorphous structure production processes to preserve the amorphous structure.
5. Bond strength, corrosion, and thermal properties can be improved by optimizing the production parameters of amorphous brazing foils.
6. The joints made with MBF-51 foil produced very different microstructures. Good mechanical and metallurgical bonding were established between the base metal and filler metals.

As a result, improved foil production parameters and joining processes made it possible to join dissimilar steel materials with high-temperature resistance, microstructural stability, high strength, and high ductility.

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