Proceedings of the World Congress on Mechanical, Chemical, and Material Engineering (MCM 2015)
Barcelona, Spain – July 20-21, 2015
Paper No. 322

Transient Liquid Phase Bonding of Dual Phase Ferrite-Martensite Steels During Dual Phase Heat Treatment Cycle

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Abstract -A low carbon-manganese steel (St52) plate was used in this research. Samples ($12\times12\times6mm^3$) for joining were cut from the received plate. Transient liquid phase diffusion bonding (TLP) was carried out at 1180℃ for different holding time, using Fe-38Ni-18B-4Mo interlayer. Microstructure studies of joints made at different holding time upto 35 Min showed a eutectic phase at the joints center lines, but increasing the bonding time to 50 Min removed this eutectic phase completely. Bonds made at this condition, 1180℃ and 50 Min, were homogenized at 725℃ for 60Min. During the homogenization heat treatment dual phase ferrite- martensite steel with 0.24 volume fraction of martensite were produced. Line scan EDS analysis across the bond region showed more uniform distribution of alloying elements in homogenized condition as compared with that of unhomogenized bond. Shear strength of bonds made at 1180℃ for 50 Min and then homogenized was about 98% that of the parent alloy ferrite – martensite dual phase steel. Micro hardness profile across the bond region showed increase of hardness in the joint zone after joint homogenization.

Keywords: TLP bonding, dual phase steels, microstructure, mechanical properties, Joint

1. Introduction

Dual phase steels containing a hard phase (martensite or bainite) and a softer matrix (ferrite) has been produced during the past few decades (liedl and Werner, 2002, sun and Pugh 2002). These steels have a good combination of high strength and good ductility, continuous yielding, high initial work hardening rate, and a low yield to tensile strength. Use of dual phase steels in high strength applications such as automotive and aerospace industries is due to their superior mechanical properties and reduced cost (Chen et al 1987). Many researchers worked on the effects of martensite volume fraction (Al-Abbasi and Nemes 2009) and martensite morphologies (Molaei and Ekrami 2009, Dallali and Shafyei 2009) on mechanical properties and work hardening behavior of these steels (Akbarpour and Ekrami 2008, Decline and Brechet 2007).

Welding of dual phase steels is unavoidable, due to their wide range of applications. But severe changes in microstructure and properties of these steels during welding should be considered. It has been reported that heat input during welding produces a soft zone which is detrimental to the weld zone

Table. 1. Chemical composition (Wt%) of used materials

steel	C	Si	Mn	P	S	Fe
	0.16	0.32	1.39	0.022	0.006	Balance
interlayer	Ni	Mo	B	Fe		
	44.23	7.61	3.86	Balance		

strength (Ramazani et al 2013, Wan et al 2014, Farabi et al 2010, Saha et al 2014, Farabi et al 2011). The most important results on welding of dual phase steels by different fusion welding techniques are producing the inhomogeneous microstructure, due to the heat input, and reducing the tensile strength, ductility and fatigue strength.

Transient liquid phase (TLP) diffusion bonding, which also called diffusion brazing, has been successfully used for joining metallic (Pouranvari et al. 2013. Elthalabawy and Khan 2010) and nonmetallic materials (Zhang et al 2002. Kim et al 2003). In this method, a filler alloy of an alloying metal containing a melting point depressant (MPD) is placed between the two surfaces to be joined, and the entire assembly is heated to bonding temperature. At this temperature, the filler alloy melts or reacts with the base metal (BM) to form a liquid phase. Generally, three distinct processes including BM dissolution, isothermal solidification and solid state homogenization will occur after liquid phase formation. Combining isothermal solidification with a subsequent solid-state homogenization treatment, offers the possibility of producing ideal joints.

The aim of this research is joining dual phase steels using TLP bonding and producing a joint with strength similar to that of the base metal. Producing the dual phase microstructure, ferrite – martensite, during bonding process was also considered.

2. Experimental Techniques

A low carbon – manganese steel plate, with chemical composition given in table 1, was used as a parent alloy. 12mm×12mm×6mm coupons were sectioned. Contact surfaces were ground using 1000 grade SiC paper and cleaned ultrasonically in methanol bath before bonding. An amorphous iron base interlayer, with 40 μm thickness, was inserted between two parent alloy coupons. Chemical composition of interlayer is also given in table 1. A fixture was used to fix the coupons, holding the sandwich assembly, and reducing the metal flow during the TLP operation. TLP bonding was carried out at 1180˚C for different holding time and then cooled in air. The bonded samples were homogenized at 725˚C for 60 min and then quenched into cold water. This homogenization heat treatment cycle also results in a ferrite – 24% martensite microstructure.

The bonded samples were sectioned perpendicular to the joint interface, polished, and etched with nital 2 and 10%. Bonds region and parent alloy microstructure were studied, using optical and scanning electron microscopes.

Microhardness test was used to determine the joint region hardness profile. The test was conducted on samples cross sections using a 25 g load on a Buehler microhardness tester. Room temperature shear test was performed employing a Santam tensile machine with a cross-head speed of 1 mm/min. The edge effects of bonded samples were removed by machining to 10mm×10mm×10mm dimension before the shear test. A fixture was used to apply shear stress on the joint during the tensile test. Three tests were carried out and the mean test result was used. This fixture subjects the sample to a pure shear stress at the bond line. A metal sleeve was placed over the fixture in order to allow no movement of the specimens. For comparison, the shear test was also conducted on the dual phase ferrite – martensite steel produced at the same heat treatment cycle used for TLP bonding.

3. Results and Discussion

3. 1. Microstructure Studies

Figure 1 shows microstructure of bond made at 1180˚C for 1 min. As can be seen, there is a eutectic phase at the center line of the joint region. This means that isothermal solidification is not completed at the bonding time of 1min. Isothermal solidification occurs due to the diffusion of boron from the melt into the parent alloy. That is, the holding time of 1 min is not sufficient for complete isothermal solidification. Figure 2 shows the scanning electron microscope photograph of this joint region in the back scattered electron condition. Three different phases are seen in this photograph. Two phases, A and B, are related to the athermal solidified region in the center line of joint and the third one, C, is the phase in the isothermal solidified region. Point analysis of phase A is shown in figure 3. B and Fe are present in this phase. Therefore it is expected that the eutectic reaction results in iron borides. According to binary phase diagram of Fe-B (Yilmaz and Ekici 2008) a eutectic transformation occurs at 1177˚C and 0.18

mole of B which results in BFe_2 phase. Since the bonding temperature was 1180˚C, therefore the eutectic phase in the joint centerline should be BFe_2.

Figure 3 also shows that C and Mn diffused from the parent alloy to the melted interlayer. The amount of Mo and Ni are reduced in the retained melt, confirming the diffusion of these elements from melted interlayer into the parent alloy. Point analysis of phase B in figure 2 showed the presence of Boron and high amount of Fe and Mo in this phase. This phase is probably borides of Fe and Mo, i.e. $FeMo_2B_2$ or $FeMo_2B_4$. Phase C point analysis showed less boron content in this phase, in comparison to phases A and B. As mentioned previously, this phase resulted from isothermal solidification. Isothermal solidification occurs as a result of boron, melting point depressant element, diffusion from melt to the parent alloy. Diffusion of boron from the melt into the parent alloy increases the melting point and isothermal solidification occurs at the bonding temperature. With respect to the Fe and Ni contents of phase C and considering the Fe – Ni binary diagram (Chuang et al. 1986), this phase is iron nickel γ solid solution at the bonding temperature which isothermally solidified and contains other alloying elements as well.

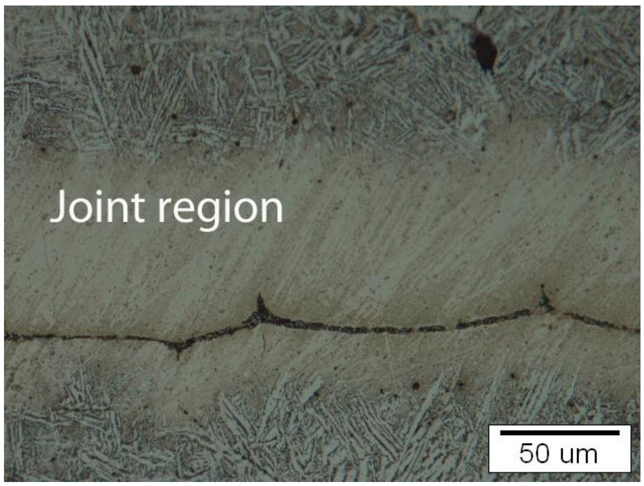


Fig. 1. Microstructure of bond made at 1180˚C for 1 min.

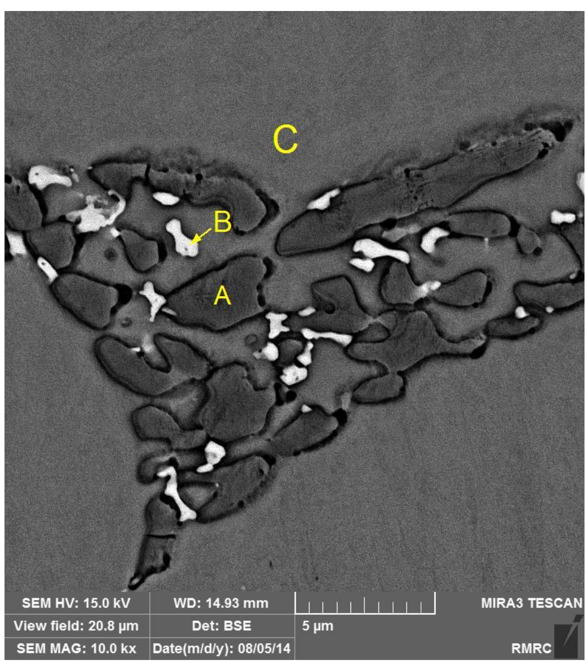
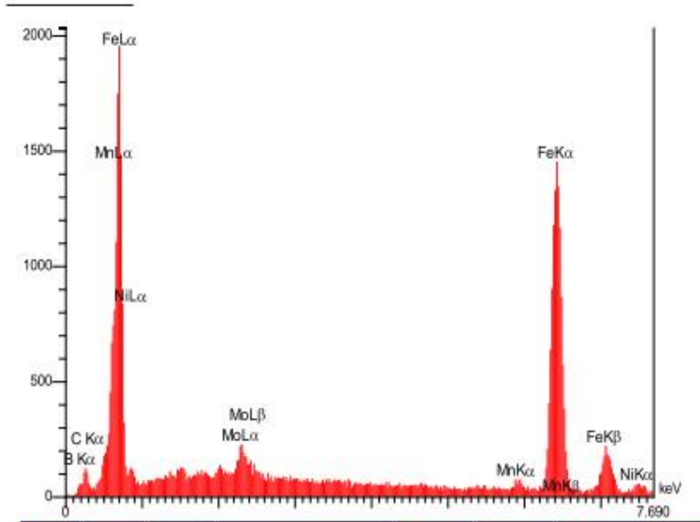


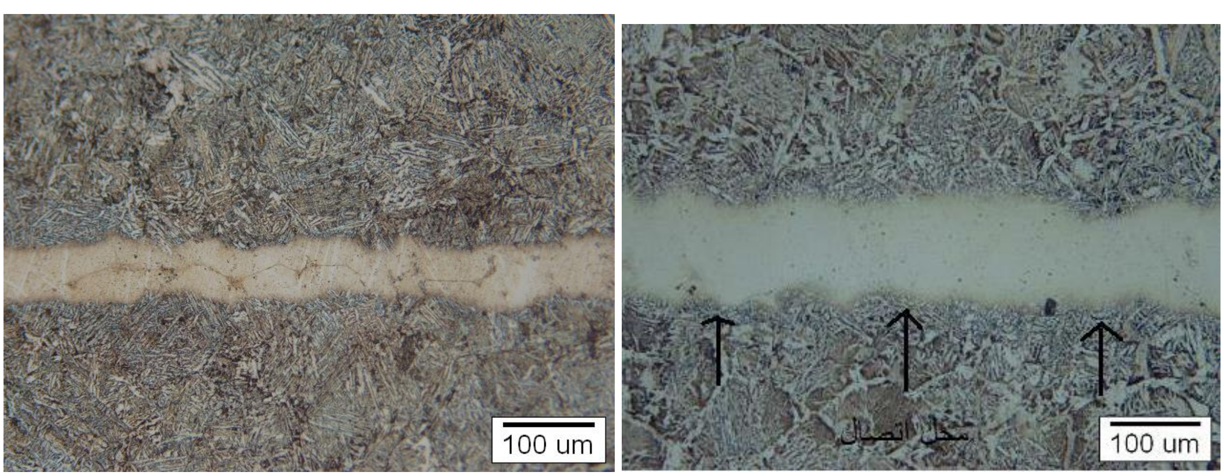
Fig. 2 SEM photograph of joint region in the back scattered electron condition.



Elt	Line	Int	Error	K	Kr	W%	A%	ZAF
B	Ka	6.5	9.8473	0.0523	0.0362	17.69	41.69	0.2047
C	Ka	24.4	9.8473	0.0326	0.0226	12.87	27.29	0.1755
Mn	Ka	12.8	0.6675	0.0122	0.0085	0.90	0.42	0.9358
Fe	Ka	724.8	0.6675	0.8406	0.5817	63.27	28.86	0.9194
Ni	Ka	14.5	0.6675	0.0263	0.0182	2.06	0.90	0.8809
Mo	La	51.5	1.9468	0.0360	0.0249	3.20	0.85	0.7775
				1.0000	0.6921	100.00	100.00	

Fig. 3. Point analysis of phase A in figure 2.

The amount of eutectic phase, at the joint center line, decreased with increasing the bonding time at 1180˚C. Microstructure of bonds made at 1180˚C for bonding time of 35 and 50 min are shown in figures 4a and 4b respectively. As can be seen from figure 4a, in joint region of bond made at 1180˚C for 35 min there is still some eutectic phase. But increasing the bonding time to 50 min caused complete removal of eutectic phase (figure 4b). This means, at this bonding time, isothermal solidification completed.



(a) (b)

Fig. 4. Microstructure of bonds made at a) 1180˚C, 35 min and b) 1180˚C, 50 Min.

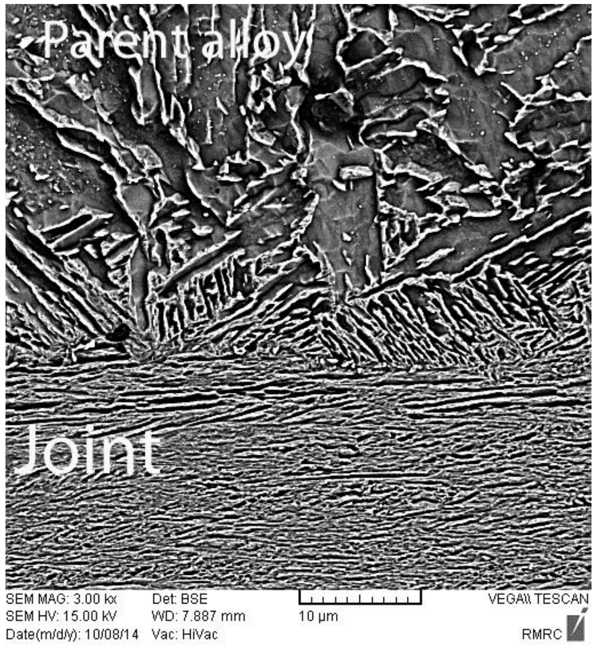


Fig. 5. Microstructure of bond made at 1180˚C for 50 min and homogenized at 725˚C for 60 min and then quenched into cold water.

3. 2. Post-Bond Heat Treatment

The last step of TLP bonding is bond homogenization. For homogenization of bond region and bring about compositional and microstructural homogeneity with that of the parent alloy, the bonds can be heated at the bonding temperature or another temperature. In this research, the post-bond heat treatment temperature was chosen as a temperature to produce dual phase ferrite – martensite microstructure in parent alloy. Samples bonded at 1180˚C for 50 min were heated at 725˚C for 60 min and then quenched into cold water. Microstructure of parent alloy after this heat treatment is shown in figure 5. Volume fraction of martensite was measured and it was about 0.24. Joint microstructure is also shown in figure 5. According to binary diagram of Fe-Ni, at the post- bond heat treatment temperature, 725˚ C, bond microstructure is a γ(Fe, Ni) solid solution which transforms to martensite after quenching into cold water. To reveal parent alloy microstructure, the bonded and homogenized samples were etched in Nital 2%. But for joint microstructure the samples were etched by Nital 10%.

Figure 6 shows line scan analysis of alloying elements in joint region and parent alloy. As can be seen, after post – bond heat treatment, distribution of alloying elements is more uniform. But, distribution map of Ni showed that for uniform distribution of this element post – bond heat treatment time should be longer.

3. 3. Mechanical Properties

Figure 7 shows variation of hardness across the joint region. As can be seen, the hardness at the joint centre is high but it decreases with increasing distance from the bond centre and becomes constant at the parent alloy region. The hardness of bond made at 1180℃ for 1 minute is greater than that of made at 1180℃ for 50 minutes at the joint region. This can be related to the existence of eutectic phase at the joint region (figure 2) and less diffusion of depressant element, B, and alloying elements from the joint to the parent alloy due to the shorter time of bonding. As mentioned in section 3.1, increasing the bonding time to 50 minutes caused complete isothermal solidification, seen from figure 4b, due to the diffusion of B from melted interlayer in to the parent alloy and cause more uniform distribution of alloying elements. Homogenization of bond made at 1180℃ for 50 minutes caused hardness increment of joint region in comparison to the unhomogenized bond. As can be seen from figure 5, joint microstructure is fine martensite, after quenching into cold water, which can cause hardness increment. Furthermore homogenization heat treatment results in more uniform distribution of alloying elements between joint region and parent alloy which can contribute to the hardness increment. For example, diffusion of C from parent alloy to the joint region (figure 6).

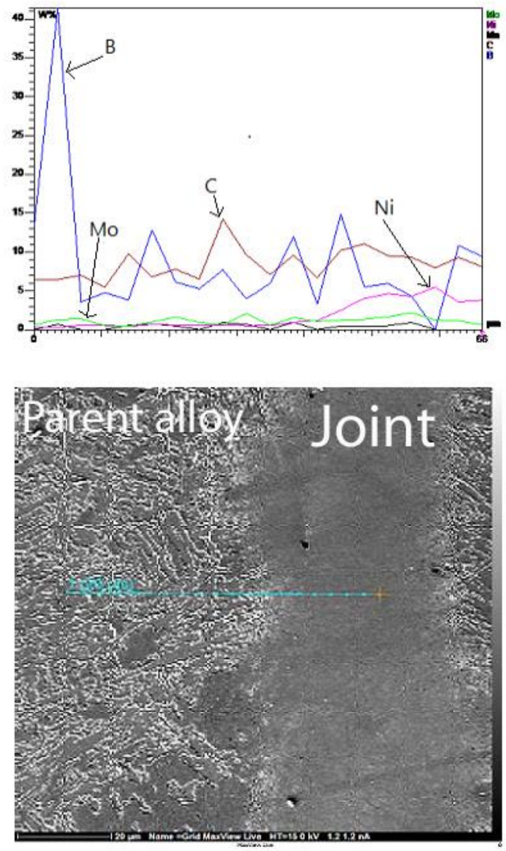


Fig. 6. Line scan analysis of alloying elements in joint region and parent alloy.

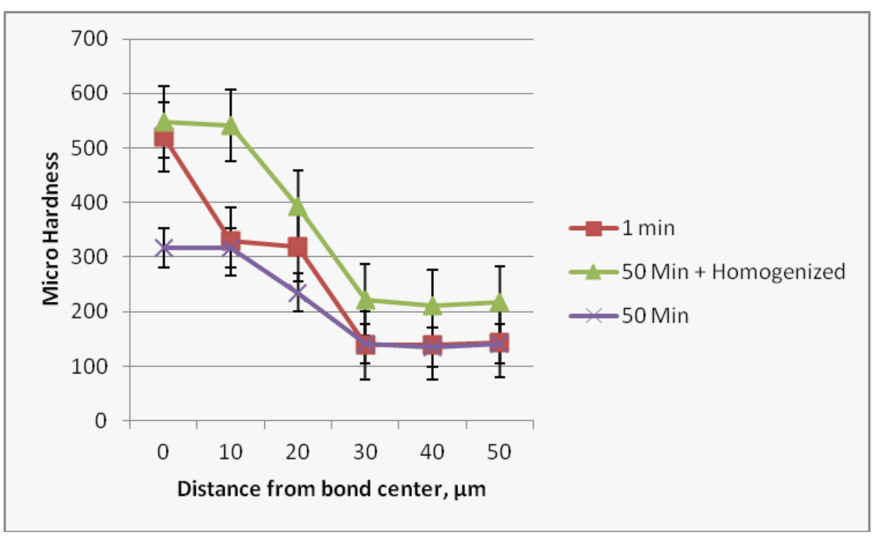


Fig. 7. Variation of microhardness with distance from the bond centre.

Figure 7 also shows that parent alloy hardness increases as a result of homogenization heat treatment. As shown in figure 5, parent alloy microstructure is ferrite with about 0.24 volume fraction of martensite, while parent alloy microstructure was ferrite and perlite before homogenization heat treatment. Therefore hardness increment due to homogenization treatment can be related to the change in microstructure from ferrite- perlite to ferrite-martnsite.

Shear test results showed that the average shear strength of bond made at 1180℃ for 50 min. and then homogenized at 725℃ for 60 min is about 515 MPa and the shear strength of parent alloy (ferrite-0.24 martensite) at the same heat treatment cycle is about 525 MPa. This means the shear strength of bond is about 98% that of the parent alloy.

4. Conclusion

A low carbon - manganese steel was joint by transient liquid phase diffusion bonding at 1180℃ for different holding time. During the bond homogenization heat treatment, the parent alloy microstructure changed to ferrite and martensite. Microstructure studies of bonded samples and mechanical test results showed that:

1. Complete isothermal solidification of joint region occurred at the bonding time of 50 min. Intermetallic compounds were observed at the joint microstructure of bonds made with holding time of 35 min and less.
2. Alloying elements distribution map showed that for uniform distribution of Ni, homogenization time of 60 min at 725˚C is not sufficient.
3. Joint region microhardness decreased with increasing the bonding time. But with the introduction of homogenization heat treatment in bonds made at 1180℃ for 50 Min, the joint and parent alloy hardness increased.
4. Shear strength of bond made at 1180℃ for 50 min and then homogenized at 725℃ for 60 min was about 98% that of the parent alloy dual phase ferrite – martensite steel produced at the same heat treatment cycle.

Acknowledgment

The authors would like to thank Sharif University of Technology for financial support of this research.

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