Research Article

Fracture Surface Analysis in Thixojoined Tool Steels

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Thixojoining has been developed for D2 and M2 tool steels. The suitable globular microstructure and excellent bonding quality are obtained through this work. Scanning electron microscopy (SEM) observation along the joint interfaces showed a smooth transition zone with no cracks. In addition, fracture surface of the shear test samples showed that the fracture mode was transgranular. Finally, based on obtained results, this method presented high quality joint with nonequilibrium diffusion interface.

1. Introduction

AISI D2 and M2 steels have good strength and excellent resistance to wear as well as perfect toughness [1]. The cladding and coating form of these tool alloys as a multilayer structure is a new type composite improved both alloys properties and is suitable for chemical and mechanical conditions. In such conditions, because of high carbon content and high mechanical properties, conventional cladding methods are not applicable or need to huge equipment [2, 3]; therefore, Thixoprocessing is recommended as a good solution in comparison with the above mentioned. Due to rheological advantages of Thixotropic materials, various methods based on Thixoprocessing have been developed. Thixojoining process is a joining technique together with forming in Thixoprocessing category. Producing multimaterial functional components and minimizing the defects over the weld zone are considered as advantages of this technique in comparison with conventional joining methods [4, 5].

This work aimed to evaluate the novel idea to achieve additional information about the general characteristics of this type of joining. In this study, bonding of two AISI tool (i.e., M2 and D2) steels has been successfully performed and characterized.

2. Experimental Procedure

Two steel grades, S600 (AISI M2) and K110 (AISI D2), were chosen in this research. These steels were used in as-received

condition without any modifications. For steel grades, initial process to produce spherical particles is less needed compared to nonferrous alloys [6]. The present work aims to provide globular joining structure in semisolid state by employing AISI D2 and M2 tool steels via applying an approximately 1 MPa constant compressive stress at nil strength temperature [7, 8] of D2 and direct partial remelting in furnace with argon controlled atmosphere. The study is known as a new type of diffusion interfacial structure across the interface of the welded parts. The direct partial remelting experiment was performed using PLC controlled resistance furnace, and a protective atmosphere was produced by flowing argon gas thorough hollow cylinder of quartz. The effect of shape factor and holding temperature has been studied by microstructural analysis to predict the heating strategy. Because of the low melting range of AISI D2 steel, the shape factor and holding temperature of this alloy was studied to determine the suitable microstructure and semisolid Thixojoining range. Therefore, the experiments have been carried out under argon atmosphere at 1280°C to 1340°C (with interval of 20°C) for 5 to 20 min holding times (with interval of 5 min). The heating rate in these experiments was 20°C/min. According to data obtained and presented in Table 1, Thixojoining experiments were finally carried out at temperatures 1280°C and 1300°C because of better obtained results. The multilayer structure samples are sectioned for testing interface strength based on ASTM SA-263 and also used for metallographic observation by SEM/EDS in Thixojoining condition without any heat

TABLE 1: Microstructural data as a function of holding time and temperature of AISI D2 steel.

Temp. (°C)	Holding time (min.)	Liquid fraction (%fl)	Shape factor (SF)	Ave. Grains size (μm)
1280	5	12	0.8	35
	10	15	0.85	50
	15	17	0.8	55
	20	18	0.78	65
1300	5	15	0.86	40
	10	18	0.85	45
	15	25	0.78	50
	20	26	0.75	55
1320	5	25	0.74	50
	10	30	0.7	50
	15	36	0.68	60
	20	36	0.7	75
1340	5	35	0.45	55
	10	37	0.4	60
	15	38	0.41	65
	20	40	0.3	80

treatment. In addition, scanning Vickers hardness map was carried out on $3 \times 3 \text{ mm}^2$ sections of Thixojoining interface.

3. Results and Discussion

In thixojoined dissimilar alloys, the alloy with low solidus temperature in the semisolid overlap zone is highly affected by temperature experiment. This is due to high values of liquid phase generation in microstructure. Based on this concept, microstructure investigation for Thixojoining temperature adjustment is focused around the solidus temperature of AISI D2 steel. Data obtained from metallographic investigations are shown in Table 1. The shape factor (SF) is calculated by using Bergsma equation [9]. Therefore, the spherical solid particles ($\text{SF} > 0.75$) generation is limited up to 1300°C . Thus, the suitable temperature range for Thixojoining was detected in 1280°C to 1300°C range. On the other hand, the microstructure study of AISI M2 steel confirmed that the selected temperature which is related to M_6C carbide dissolution and stable liquid phase content has been produced in this temperature range [10]. Then, Thixojoining has been done in temperatures 1280°C and 1300°C and the scanning hardness maps of the joint interface were obtained for more clarification. The results of interface microstructures and hardness map are shown in Figure 1. As can be seen in these figures, the graded shape hardness profiles show increasing from AISI D2 steel sides to AISI M2 steel sides, which is related to nonequilibrium diffusion zones of alloy elements. The interval distance between each two points of hardness in 2-D is $200 \mu\text{m}$. More information about this procedure can be found in [11].

Secondary carbides precipitation depends on the cooling rate from Thixojoining temperatures and strongly influences the as-quenched microstructures. The maximum and minimum values of hardness are related to 1300°C temperature. This is due to dissolution and transformation of M_7C_3 carbides in AISI D2 steel and M_6C and M_3C carbides in AISI M2 steel [10]. Increasing dissolution carbides in matrix

TABLE 2: Shear test results of Thixojoining samples.

Thixojoining temperature	Stress/strain in max. load ($\sigma_{\text{uts}}, \epsilon_u$)	Stress/strain in fracture point (σ_f, ϵ_f)
1280°C	$360 \pm 5 \text{ MPa}/2.5$	$290 \pm 10 \text{ MPa}/3.4$
1300°C	$470 \pm 10 \text{ MPa}/2$	$420 \pm 5 \text{ MPa}/2.6$

leads to carbides transformation especially to complex M_{23}C_6 carbides and increases hardness. As Figure 1(a) shows, the lower amount of liquid phase in 1280°C is beneficial since sliding of the steel surface on interface is limited. Figure 1(b) shows an increase in size of AISI D2 solid particles as the liquid phase increases. The increase in liquid phase leads to less friction between the joining samples and sliding of surfaces on each other which produce ledeburitic phase coalescence in interface [11, 12].

The shear test of Thixojoining parts showed the high bonding strength interface in 1300°C (Table 2) but as it is shown in this table the fracture strain or displacement in 1300°C is lower than 1280°C temperature. These are related to carbides dissolution increasing in 1300°C which is decreasing the fracture strain. In 1300°C , the complex carbides and microvoids are produced.

These caused the increasing maximum load and decreasing fracture displacement in comparison with 1280°C temperature. The larger, primary carbides found in high-alloy steels act as stress raisers to initiate the micropitting mode of contact fatigue under wear situations. Microstructural alterations research has shown that contact fatigue life increases as the size of carbides decreases. In addition, double quenching produces a refined microstructure that also increases material toughness and fatigue resistance. The development of strength and toughness in these steels is linked to such factors as the size and distribution of carbides, relative proportions of martensite and austenite phases, and grain size.

FIGURE 1: SEM microstructure of interfaces and microhardness map in (a) 1280°C and (b) 1300°C.

FIGURE 2: Fracture surface of Thixojoining samples in (a) 1280°C and (b) 1300°C.

An important weakness of these highly alloyed materials is their fracture toughness. In Thixojoining situations carbides size and globular microstructure are helped to improvement of interface mechanical properties. By focus on this Thixojoining advantage, fracture surface of shear test specimens has been studied by SEM/EDS. In Figures 2(a)-2(b), the fracture surfaces of two Thixojoining samples are shown. The SEM/EDS analyses show crack formation in laminated Cr-rich carbide areas in fracture surface, which can play a role as stress concentration points. This laminated Cr-rich carbide is produced from peritectic reaction of solid particles surrounded by liquid phase. Liquid phase is produced in the

semisolid range and can be reacted with austenite phase, and this led to generation of carbides and a new solid layer around the grains (see Figures 2(a)-2(b)). The result of the defect survey in fracture surface shows the microvoids in beside the solid particle sliding zone, which are shown in Figures 3(a)-3(b). As it is shown in Figure 3(a), the microvoids are produced when the solid particle grain is slid in a liquid bed at the semisolid range. Detection probability of this type of defect in SEM microstructure analysis of the interface is very low, but detection in fracture surface is simple, because fracture occurs in the weak surface. By focusing on microvoid location (Figure 3(a)), two zones are detected. The circular

FIGURE 3: (a) Microvoids and (b) microcracks in fracture surface of Thixojoining sample in 1300°C.

FIGURE 4: EDS analysis of (a) spectrum 1 in Figure 3(a) and (b) spectrum 3 in Figure 3(b).

shape carbide at the interface of two spherical solid particles is identified, which is parallel with shear force (see Spectrum 1 in Figure 3(a), where the elements Wt% of EDS analysis in this point are 49.1%Fe, 7.7%Cr, 19.8%W, 16.2%Mo, 4.9%V, and 2.3%C) and in another zone is perpendicular to the force (see Spectrum 2 in Figure 3(b), where the elements Wt% of EDS

analysis in this point are similar to Spectrum 1 in Figure 3(a) and are 51%Fe, 7.1%Cr, 18.2%W, 16.8%Mo, 4.5%V, and 2.4%C).

Figures 4(a) and 4(b) show the EDS spectrum peaks of Spectrums 1 and 3 of Figures 3(a) and 3(b). In the shear test condition, disbanding of the solid particles has occurred as well as several microcracks with nano wide which are found

out in fracture surface. On the other hand, solid layers around the grains are recognizable in Figure 3(b) with Spectrum 3 as example, in which the elements Wt% of EDS analysis in this point are 82.7%Fe, 6.2%Cr, 1.65%W, 5%Mo, 3.05%V, and 1.4%C.

4. Conclusions

Joining interface was studied by SEM/EDS analysis which demonstrated a suitable joint without any flaws. The mechanical properties of the joint interface were carried out by shear test and Vickers scanning microhardness map, representing a high bonding strength. Laminate changes in hardness maps which are represented diffusion of elements and are confirmed with carbides dissolution. The results obtained from investigations proved a good joining quality. The current work confirmed that a joint with suitable globular microstructure and high bonding quality components can be obtained in 1300°C. Based on the results obtained from this study, a novel method is introduced which leads to a high quality joint with nonequilibrium diffusion interface.

Conflict of Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

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