Title	Dissimilar Welding of Titanium Alloys to Steels
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Citation	Transactions of JWRI. 2012, 41(2), p. 7-12
Version Type	VoR
URL	https://doi.org/10.18910/24860
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Dissimilar Welding of Titanium Alloys to Steels†

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Abstract

This review summarizes the dissimilar welding of titanium alloys to steels over a period of ten recent years, involving the welding processes which are used for the dissimilar welding of titanium alloys to steels, the mechanical properties of the joints and the discussion for the forming mechanism of the interface. Reducing the formation of brittle intermetallic compound (IMC) is a key requirement in the dissimilar welding of titanium alloys to steels, because the strength of the welding joints depends on the presence of IMC.

KEY WORDS: (Dissimilar welding), (Titanium alloys), (Steels), (IMC), (Welding process)

1. Introduction

In recent years, joining of dissimilar materials was gradually investigated because it is capable of offering complex functions and finding applications in variety of fields such as thermal power station, nuclear industries, petrochemical industries, aerospace, microelectronics, automobile etc. For example, aluminum and magnesium alloys are used by automobile industries because they are attractive as lightweight structural materials to achieve high performance and efficiency. However, steels are still widely used as structural materials due to their high absolute strength and good cost efficiency. Therefore, it is becoming very important to join Al or Mg alloys to steels to fabricate structural components, and dissimilar welding technology is necessary.

Until this paper, because of the purpose of lightweight and save cost, many researchers have done a lot of work to join Al or Mg alloys to steels. But there are few works to study the dissimilar joining of titanium alloys to steels. Titanium alloys have good features such as high specific strength, good high temperature mechanical properties and excellent corrosion resistance, thus have been applied in aerospace, transportation, power generation and chemical industries. However, wider use of these materials is limited by their expense. One solution is to join titanium alloys to low-priced conventional steels by which the usage of titanium alloys can be reduced.

The major metallurgical problem of joining titanium alloys with steels consists in formation of brittle intermetallic phases, FeTi and Fe_2Ti, as shown in **Fig.1** [1], which make impossible direct joining by conventional welding methods. To solve this problem, researchers have tried many welding joining processes in the recent ten years as shown in **Table.1** They are classified into two process groups of solid-state joining process [2-17] and high energy beam welding process [18-22]. The former process as such as diffusion bonding, explosive welding, friction welding and friction stir welding have the feature of a lower joining temperature and the latter such as electron beam welding, laser welding have a feature of reducing the heat affection and the suppressing the mixing of each material. This paper will discuss the welding processes respectively with typical research examples.

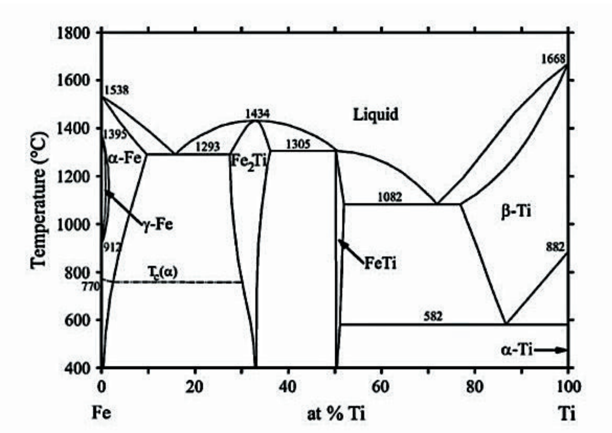

Fig.1 Ti-Fe binary phase diagram. [1]

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Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

Table.1 Dissimilar welding researches of titanium alloys to steels over a period of recent ten years.

No	Date	Authors	Materials	Method
1	2012	Zhang et al.	Ti-15V-3Al alloy to 304 SS	Electron beam welding
2	2012	Shanmugarajan et al.	CP Ti to 304 SS	Laser welding
3	2012	Gao et al.	Ti-6Al-4V to 304L SS	Laser welding
4	2011	Tomashchuk et al.	Ti-6Al-4V to 316L SS	Laser welding
5	2011	Fazel-Najafabadi et al.	CP Ti to 304 SS	Friction Stir Welding
6	2011	Akbarimousavi et al.	CP Ti to 316L SS	Friction Welding
7	2010	Wang et al.	Ti-15V-3Al alloy to 304 SS	Electron beam welding
8	2010	Liao et al.	CP Ti to Steel	Friction Stir Welding
9	2010	Fazel-Najafabadi et al.	CP Ti to 304 SS	Friction Stir Welding
10	2010	Kundu et al.	CP Ti to SS	Diffusion welding
11	2009	Mousavi et al.	CP Ti to 304 SS	Explosive welding
12	2009	Elrefaey et al.	CP Ti to Steel	Diffusion welding
13	2009	Elrefaey et al.	CP Ti to Steel	Diffusion welding
14	2009	Dey et al.	CP Ti to 304L SS	Friction welding
15	2008	He et al.	Ti-6Al-4V to SS	Diffusion welding
16	2005	Kahraman et al.	Ti to SS	Explosive welding
17	2005	Ghosh et al.	Ti-6Al-4V to 304 SS	Diffusion welding
18	2005	Ghosh et al.	Ti-6Al-4V to 304 SS	Diffusion welding
19	2005	Kundu et al.	CP Ti to 304 SS	Diffusion welding
20	2004	Lee et al.	CP Ti to 321 SS	Friction welding
21	2003	Mudali et al.	CP Ti to 304 SS	Friction and explosive welding

2. Solid state joining process

2.1 Diffusion bonding

Conventional fusion welding is not a feasible technique for joining titanium alloys to steels duo to the formation of brittle intermetallic phases during the welding process. Thus, diffusion bonding as a solid-state joining technique was employed in order to avoid melting. Ghosh et al. studied the feasibility of diffusion bonding of pure titanium (CP Ti) to 304 stainless steel [13]. They kept the joining surfaces of the samples in contact with a specially designed jig and 3MPa uniaxial load was applied along the longitudinal direction. Diffusion bonding was carried out at 950˚C for 30-120min in steps of 30min. The vacuum was maintained at $(4–6)\times10^{-4}$ mbar during processing. Heating was done at the rate of 14˚C/min during joining and after bonding the samples were allowed to cool in vacuum. **Fig.2** shows the optical micrographs of the diffusion bonded couples processed at 950˚C for (a)30min, (b)60min, (c)90min and (d)90min. They found the diffusion zone in the titanium substrate has a larger width than that of 304 stainless steel side. The reaction zone contains intermetallic phases such as Fe_2Ti, Cr_2Ti, FeTi for the diffusion bonded joints. These phases are brittle and responsible for weakening the interface. **Fig.3** shows the graphical presentation of the tensile properties of the bonded joints processed at 950˚C. The maximum bond strength of 71% of that of titanium has been obtained for the couples processed for 30min, owing to the formation of finer intermetallics. An increase in bonding time promotes the growth of intermetallics and formation of voids leading to a sharp fall in strength properties of the bonded assemblies. However, no shear strength value resulted. They also tried to adjust the diffusion bonding process parameters in order to achieve a joint with optimum mechanical properties [14].

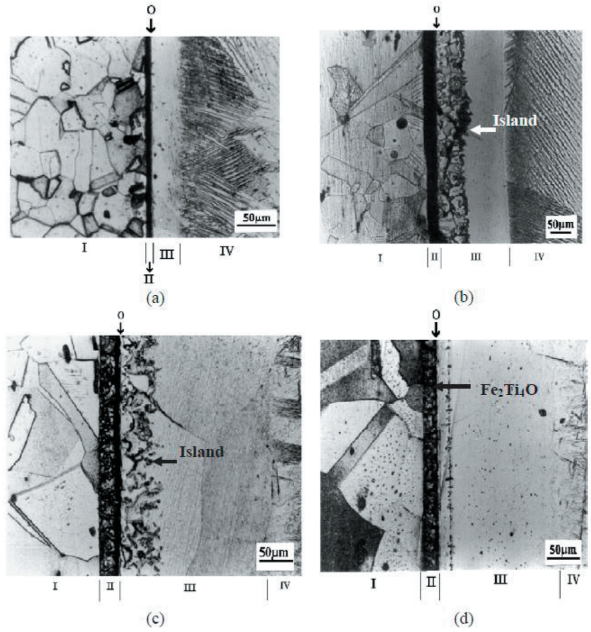

Fig.2 Optical micrographs of the diffusion bonded couples processed at 950˚C for (a) 30min, (b) 60min, (c) 90min and (d) 120min [13].

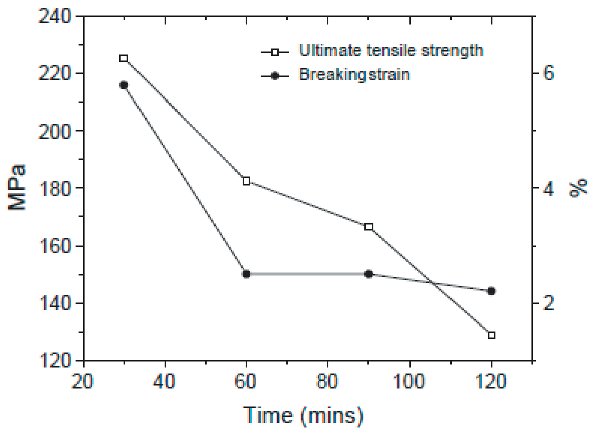

Fig.3 Graphical presentation of the tensile properties of the bonded joints processed at 950˚C [13].

On the other hand, Elrefaey et al. achieved solid state diffusion bonding of titanium (CP Ti) to steel (Low carbon steel) using a copper base alloy as interlayer[9]. The joint assembly was performed using a 2×10^{-5} Pa vacuum atmosphere and a uniaxial load of 3MPa was applied to the sample at bonding temperatures of 800˚C and 850˚C. At these bonding temperatures joints were prepared at holding times ranging from 30 to 180min. Heating and cooling rates of 15˚C/min were employed during the heating and cooling cycles. **Fig.4** shows gross-section of the titanium/copper/steel interface for the samples joined at temperature of 850˚C for (a)30min, (b)60min, (c)90min and (d)180min. Diffusion bonding of titanium to steel could not be carried out at a temperature lower than 800˚C, even at holding time of 180min. However, successful joining is achieved at 850˚C at all holding times. **Fig.5** shows the SEM image of the joints bonded at temperature of 850°C for 90min. The copper interlayer was successfully employed to prevent the mutual diffusion between iron and titanium and subsequently the hard and brittle Fe–Ti and Ti–C intermetallics were not formed in the bonded joint. In spite of the formation of Cu–Ti intermetallics at the interfacial structure, it is perhaps less detrimental on the strength of the joint than Fe–Ti intermetallics. They found that the strength increased firstly as the holding time was extended up to 90min owing to the promotion of the diffusion and coalescence of joint surfaces. With an increase in the holding time to 180min, the strength decreased because of the increased volume fraction of discontinuities and the fracture of bonded joints after the shear test took place at the titanium/copper-based interlayer owing to the formation of Ti_2Cu and TiCu intermetallics.

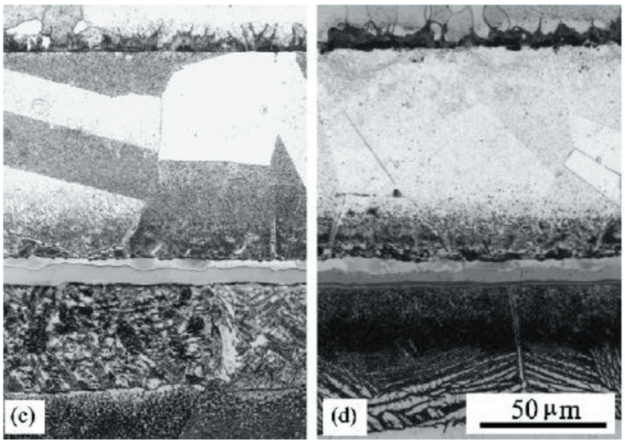

Fig.4 Cross-section of the titanium/copper/steel interface for the samples joined at temperature of 850°C for (a) 30 min, (b) 60 min, (c) 90min and (d) 180 min [9].

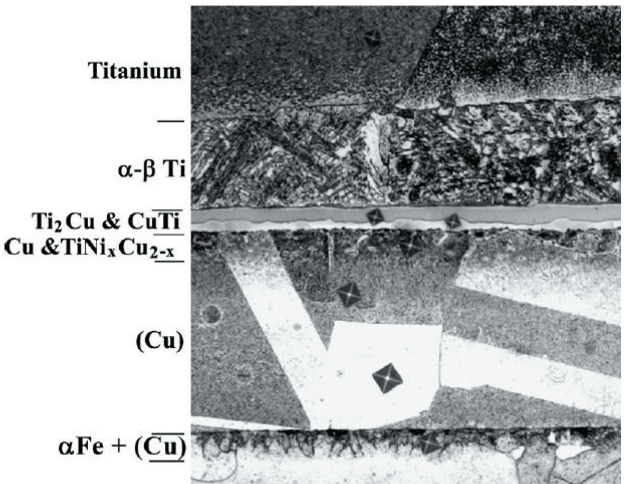

Fig.5 SEM image of the joints bonded at temperature of 850°C for 90min [9].

Although some other successful examples have been reported [6, 11, 15], however, during the diffusion bonding process, the whole metallic materials of the specimens need to be heated to the high temperature, which is not permitted in some occasions. In addition, the diffusion process needs a long time to implement in general.

2.2 Friction welding and friction stir welding

As a kind of conventional solid state joining processes, friction welding has been used for joining dissimilar metals. In friction welding, heat for welding is produced by relative motion of the two surfaces being joined, and under normal conditions no interfacial melting occurs. Dey et al have studied friction welding for joining titanium to 304L stainless steel [10]. Friction welding parameters were optimized to produce joints that are stronger than the Ti base material as confirmed by tensile tests, and tensile failure occurred in the Ti base material. **Fig.6** shows the tensile tested sample. However, the sample of friction welding can only be club-shaped and need the post-weld heat treatment to increase the bend ductility. The conditions make friction welding difficult to apply.

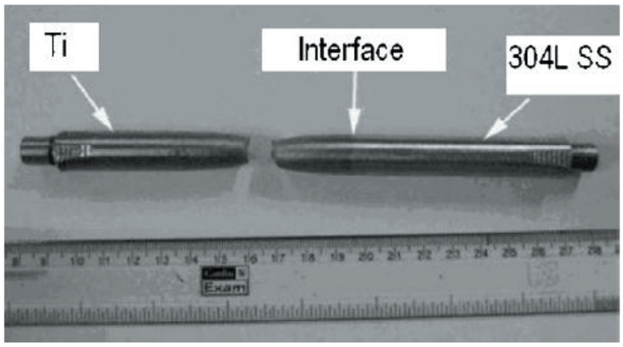

Fig.6 Tensile tested Ti/304L SS sample showing failure in the Ti base material [10].

Friction stir welding (FSW), a novel solid-state welding process developed by The Welding Institute (TWI), has several advantages such as a high operative efficiency and versatility as compared to the conventional solid-state welding processes. In early years, FSW was introduced for light alloys. Recently, high performance tool materials are employed for FSW of high melting temperature materials such as titanium, nickel and steels [23-24].

Fazel-Najafabadi et al. have studied friction stir welding technique for joining pure titanium (CP-Ti) to 304 stainless steel and achieved sound dissimilar lap joint by adjusting tool rotation and advancing speeds under the protecting atmosphere [2]. **Fig.7** shows the schematic diagram of the geometry of a dissimilar CP-Ti/304 stainless steel lap design. Lap joint with a maximum failure load of 73% of that of CP-Ti was achieved by adjusting tool rotation and advancing speeds. **Fig.8** shows failure loads of dissimilar CP-Ti/stainless steel lap joints produced using different FSW process parameters.

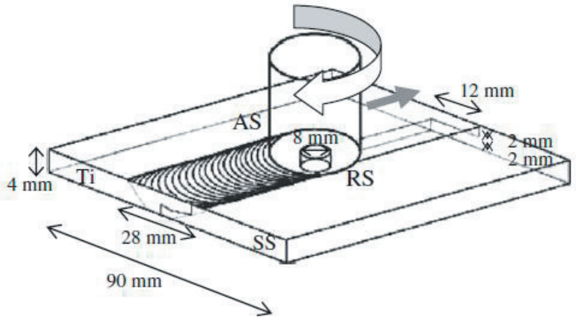

Fig.7 Schematic diagram of the geometry of a dissimilar CP-Ti/304SS lap design [2].

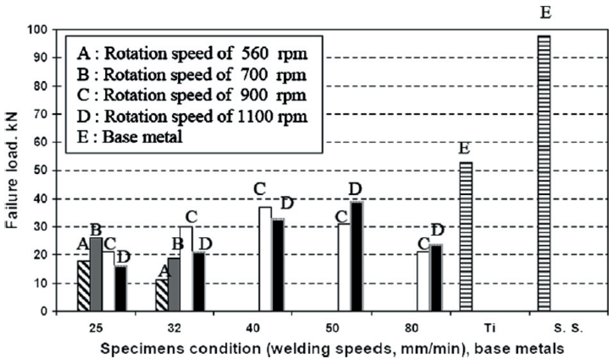

Fig.8 Failure loads of dissimilar CP-Ti/stainless steel lap joints produced using different FSW process parameters [2].

On the other hand, Liao et al. have studied microstructure at friction stir lap joint interface of pure titanium and steel [4]. Swirling like macro-and micro-intermixing zones are formed at the joint interface. **Fig.9** shows EBSD phase map of the macro-intermixing zone at the joint interface. At the macro- intermixing zones, α titanium and steel are mixed in swirling morphology; at the micro- intermixing zones, the tiny Fe–Ti intermetallic particles are dispersed and mixed with β titanium in layers, and in the area adjacent to the micro-intermixing zone, the grain size of titanium and steel becomes very small. The high tensile strength of the lap joint is supposed to be attributed to the microstructures at the joint interface.

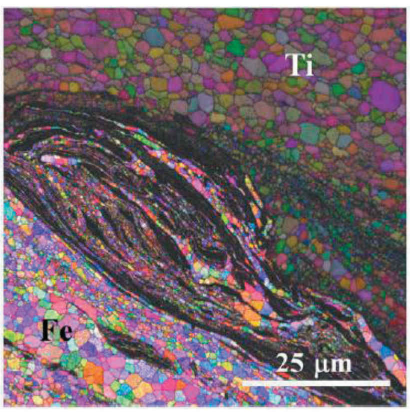

Fig.9 EBSD phase map of the macro-intermixing zone at the joint interface [4].

2.3 Explosive welding

As another kind of solid state metal joining process, explosive welding offers an excellent alternative for joining dissimilar metals and alloys with varying physical and metallurgical properties. Mousavi et al. have arrived at a suitable parametric window both analytically and experimentally for explosive welding of CP Ti–304 stainless steel [7]. They have found that explosive load had a severe impact on both the interface morphology and intermetallic formation and concluded that at low loads formation of intermetallics could be totally avoided as shown in **Fig10.** Mudali et al. studied the corrosion and bend ductility of joint between Ti dissolver and 304L stainless steel tubing by friction and explosive welding. They have found out that friction welded joints have poor bend ductility but good corrosion resistance and vice versa in explosive bonded joints [17]. Kaharaman et al. have studied the explosive bonding of Ti to 304 stainless steel with respect to explosive ratio concentrating on the interface appearance [12].

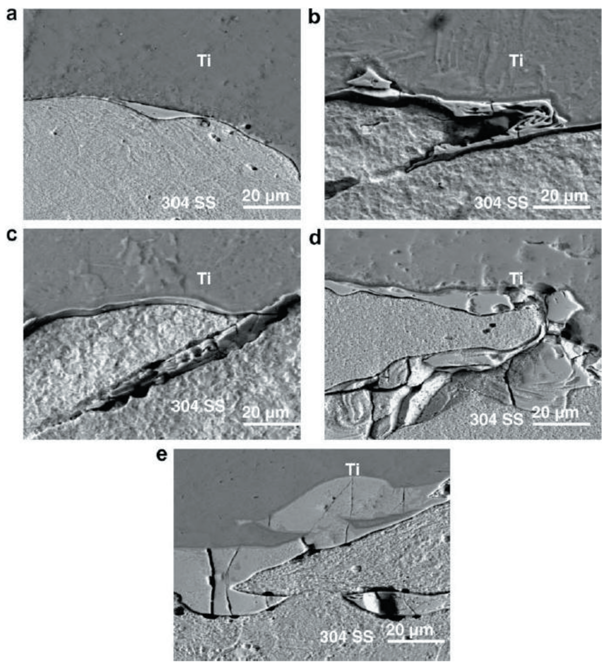

Fig.10 SEM-BSE micrographs from the interface of CP-titanium/AISI 304 stainless steel for different explosive loads: (a) R = 1, (b) R = 1.2, (c) R = 1.5, (d) R = 2.0, (e) R = 2.5 [7].

3. Electron beam welding and laser welding

Owing to the advantages of high energy density, precisely controllable heating position and radius, electron beam welding and laser welding have made great achievements in the joining of dissimilar metals [25-30].However, as fusion welding methods, they can't avoid the formation of intermetallics during the welding process of joining the titanium alloys to steels. To solve the problem, Wang et al. studied the feasibility of electron beam welding of Ti-15-3titanium alloy to 304 stainless steel with copper interlayer sheet [22]. **Fig.11** shows surface features of Ti-15-3/304 joints electron beam welded without (a) and with (b) inserting copper transition sheet. They have found that with dual pass electron beam welding with first welding between Ti and Cu sheet and second welding between Cu and stainless steel sheet, cracking could be avoided. Dispersed distribution of brittle $TiFe_2$ compound in solid solution and the narrowing of intermetallics layer were key reasons for success. **Fig.12** shows micro hardness distribution on cross section of weld zone. The highest value of micro hardness emerged in Ti-Cu and Ti-Cu-Fe compounds layer, where the welding joint ruptured complying brittle cleavage fracture mode when being stretched. Obviously, the intermetallics could not be avoided completely which has led to brittle fracture when stretched.

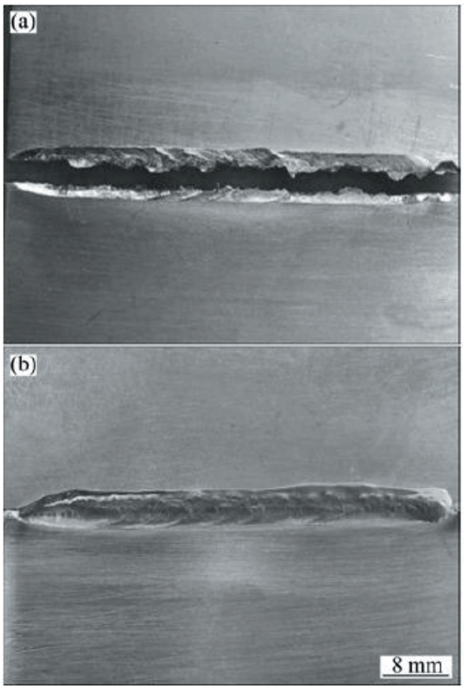

Fig.11 Surface feature of Ti-15-3/304 joints electron beam welded without (a) and with (b) inserting copper transition sheet [22].

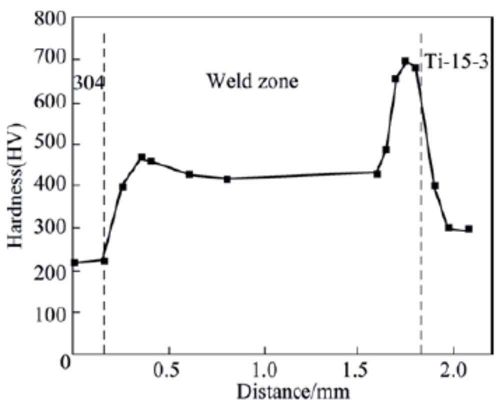

Fig.12 Microhardness distribution on cross section of weld zone [22].

On the other hand, Gao et al. developed laser welding of Ti-6Al-4V alloy to commercial AISI 304L stainless steel using Mg interlayer [20]. **Fig.13** shows bead appearance of joint. Accepted joints were obtained under the optimal welding parameters, and the cross-weld tensile strength was up to 221 MPa, recovering 94% of the commercial AZ31B Mg alloy. The interfacial layers of stainless steel/weld and Ti/weld were mainly formed by the atomic diffusion of alloying elements, but reaction diffusion happened in the Ti/weld interface due to the observation of Mg17Al12.The joints all fractured at the interfaces. **Fig.14** shows fracture surface morphologies at stainless steel side of joint fractured in stainless steel/weld interface. The fracture surface was composed of rough areas characterized by ductile–brittle fracture characteristic and smooth areas characterized by brittle fracture characteristic. By quantitative analysis, the rough areas were identified as remaining Mg weld metal, and the smooth areas were identified as Ti or stainless steel surface.

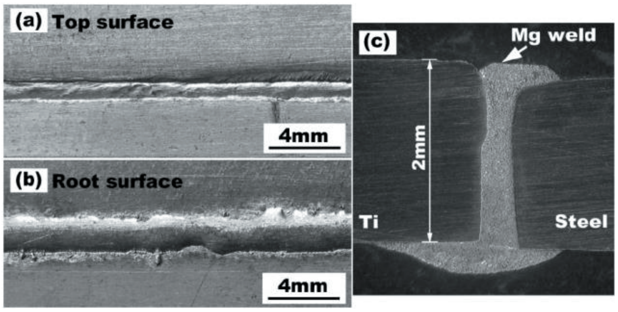

Fig.13 Bead appearance of joint. (a) top surface, (b) root surface, (c) cross-section [20].

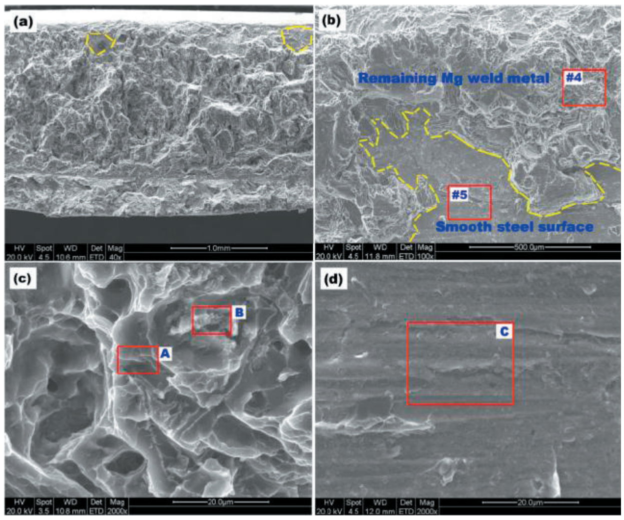

Fig.14 Fracture surface morphologies at stainless steel side of joint fractured in stainless steel/weld interface. (a) an overview; (b) details of location with large smooth area, (c) details of area 4, (d) details of area 5 [20].

4. Summary

With the wider and wider application of titanium alloys, the dissimilar welding technique for joining titanium alloys to steels will become more and more important. Among the many welding processes tried up to now, FSW is one of the most capable welding processes for dissimilar welding of titanium alloys to steels. However, there are still a lot of problems which we don't understand completely, such as the parameters of FSW for the influence of microstructure of the dissimilar joint and we need to make unremitting efforts for it in future.

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