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The influence of welding parameters on the joint strength of resistance spot-welded titanium sheets

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Abstract

In this study, commercially pure (CP) titanium sheets (ASTM Grade 2) were welded by resistance spot welding at different welding parameters and under different welding environments. The welded joints were subjected to tensile-shearing tests in order to determine the strength of the welded zones. In addition, hardness and microstructural examinations were carried out in order to examine the influence of welding parameters on the welded joints. The results showed that increasing current time and electrode force increased the tensile shearing strength and the joints obtained under the argon atmosphere gave better tensile-shearing strength. Hardness measurement results indicated that welding nugget gave the highest hardness and the heat affected zone (HAZ) and the base metal followed this. The argon gas used during the welding process was seen to have no influence on the hardness values. Microstructural examinations revealed that the deformations took place in the welding zone during welding. The twinning took place in the grains. High electrode force and high weld cycles, were used during the welding, increased the twinning.

Keywords: Resistance spot welding; Titanium; Welding parameters and twinning

1. Introduction

Titanium and its alloys have been considered as one of the best engineering metals for use in industrial applications [1]. Titanium and its alloys exhibit excellent corrosion resistance and high strength to weight ratios which make them ideal candidates for use in primarily two areas of application: corrosion resistant service and specific strength efficient structures [2]. Normally, low strength, unalloyed, commercially pure (CP) titanium is used in the fabrication of tanks, heat exchangers and reactor vessels for chemical processing, desalination and power generation plants [2,3]. Titanium undergoes an allotropic transformation at 882 °C from a hexagonal close packed crystal structure (α phase) to a body centred cubic structure (β phase) [4].

Pure titanium metal has high reactivity with oxygen [5]. Commercially pure titanium is widely used as dental implant material because of its suitable mechanical properties and excellent biocompatibility [6,7]. The latter is mainly due to its excellent corrosion behaviour in the physiological environment [6,8]. Pure titanium and other $\alpha + \beta$ titanium alloys were originally designed for use in general structural materials, specially for aerospace structures and only later adopted for biomedical applications [9].

Welding of titanium and alloys is difficult because titanium is extremely chemically reactive at high temperatures. During welding, titanium alloys pick up oxygen and nitrogen from the atmosphere easily [8]. The welding processes recommended for use when welding titanium and its alloys are; tungsten inert gas (TIG) welding, metallic inert gas (MIG) welding, resistance welding, (both spot and seam) electron beam welding [10]. Resistance welding is one of the most useful and practical methods of joint metal. This process is ideally suited to production methods [11]. The heat in resistance welding is generated by electrical

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resistance between the parts to be welded. Heat is developed using low voltage and high amperage [12,13]. Resistance welding includes spot welding, seam welding, flash welding and other similar processes that are performed on machines [14].

Resistance spot welding (RSW) is used for the fabrication of sheet metal assemblies. The process is used extensively for joining low carbon steel components. High-strength low-alloy steel, stainless steel, nickel, aluminium, titanium and copper alloys are also spot welded commercially [15]. In electric resistance spot welding. the overlapping work is positioned between the water-cooled electrodes, then the heat is obtained by passing a large electrical current for a shot period of time [16–18]. There are three stages in making spot weld first the electrodes are brought together against the metal and pressure applied before the current is turned on (Fig. 1). Next the current is turned on momentarily. This is followed by the third, or hold time in which the current is turned off but the pressure continued. The hold time forges the metal while it is cooling [19].

Welding of titanium to dissimilar metals through solid state welding processes have been performed by Kahraman [2] and Turgutlu et al. [20]. On the other hand, Ti and its alloys to each other are generally welded by laser beam welding, electron beam welding and gas tungsten arc welding [21–25]. To the best of the authors's knowledge, there is no work dealing with welding of Ti and their alloy by resistance spot welding was reported in the literature. The objective of the present work is to study the effect of spot welding parameters and the welding environment on weldability of CP Ti sheet. Microstructure, hardness and tensile shear strength of the joined metals were examined.

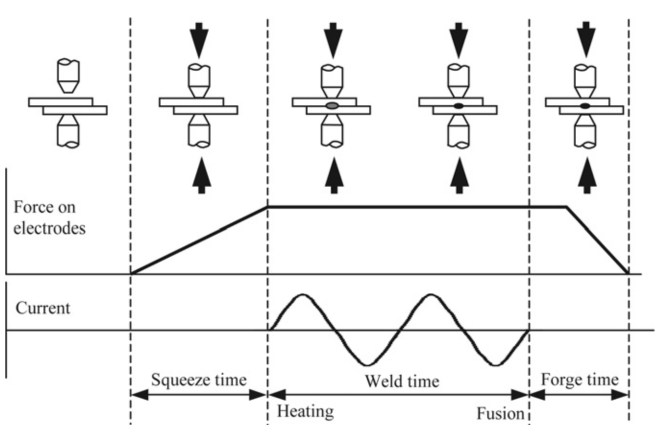

Fig. 1. Typical spot-welding cycle.

2. Experimental prodecure

In this study, commercially pure (CP) titanium (ASTM Grade 2) sheets (1.5 mm thick) were used as the base material. The CP Ti used was strengthened by the interstitial elements oxygen, nitrogen and carbon, as well as by the solid solution strengthening element, iron. Nominal chemical composition and some mechanical properties of the CP Ti sheet is given in Table 1. The CP Ti sheets were cut in the dimension of $100 \times 30 \times 1.5$ mm (Fig. 2) and their surfaces were chemically cleaned by acetone before resistance spot welding to eliminate surface contamination.

The tests were carried out using a current and time controlled electric resistance spot welding machines. This machine was equipped with a pneumatic pressure system. Welding, squeezing and holding times were adjusted with the accessories on the machine. The machine employed pure copper electrodes with 5 mm end diameter. Welding processes were carried out in a fixture shown in Fig. 3 schematically. Additionally, the photograph in Fig. 4 shows the resistance spot welding machines and its accessories.

The parameters used in the resistance spot welding of the CP Ti sheets are given in Table 2. Five joints were made at each parameter under air and argon atmospheres. After the welding, the welded specimens were removed from the machine and left cooling in open air. Welding current was kept constant (10,000 A) during the welding and electrode force, welding time and welding atmosphere were changed.

At each parameter group, four of the welded specimens were used to make tensile shear test specimen while the remaining one was used for microstructure examination and hardness measurement. For metallographic examinations, the specimens were cut mechanically and hot mounted in bakelite. After grinding using rough and fine emery and polishing, the specimens were etched in a chem-

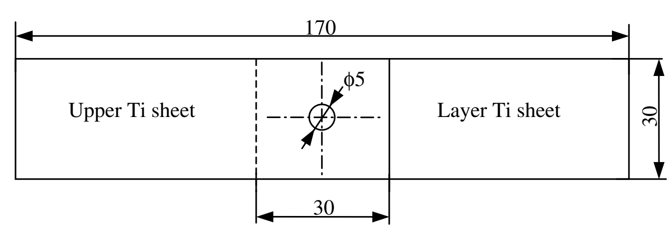

Fig. 2. Dimensions of resistance spot weld specimen (mm).

Table 1
Chemical composition and some mechanical properties of the pure Ti sheet

ASTM Standard	Yield strength	Tensile strength	Transformation temperatures (°C)		Alloying elements (% wt)				
			Alpha (α)	Beta (β)	N	C	H	Fe	O
Grade 2	280 MPa	340 MPa	913	890	0.03	0.10	0.015	0.30	0.25

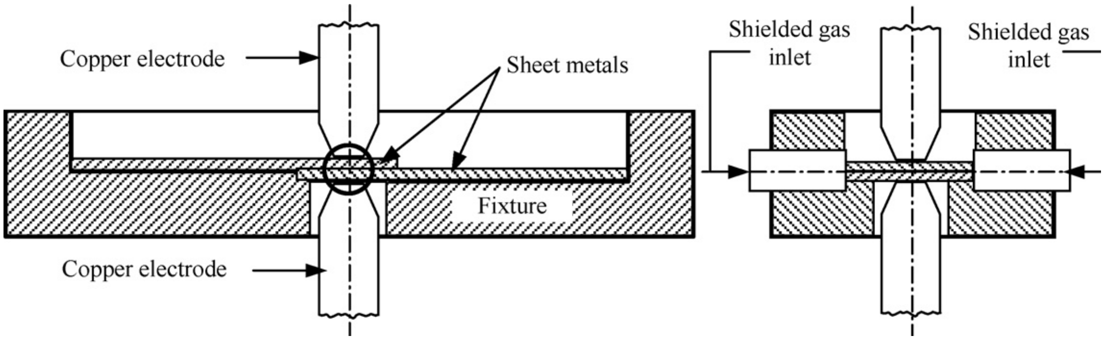

Fig. 3. Schematic illustration of fixture.

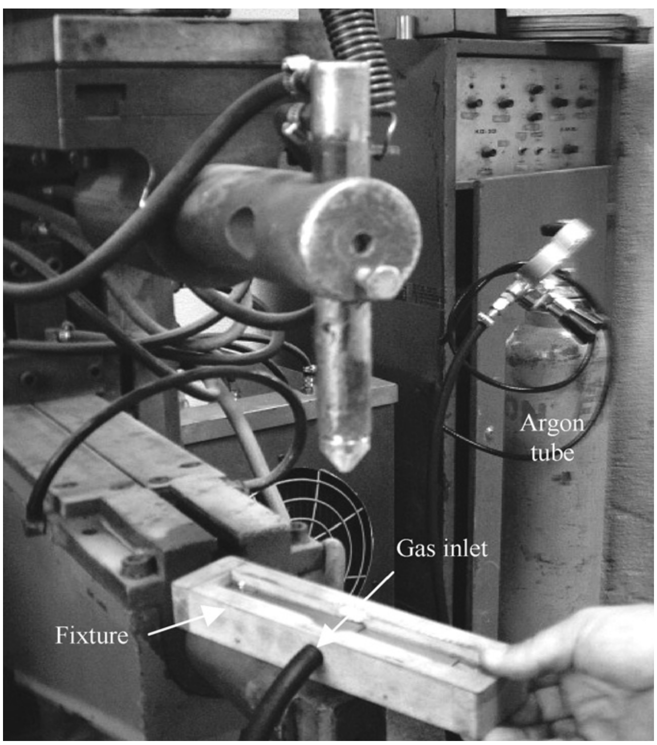

Fig. 4. Experimental system for resistance spot welding.

Table 2
Resistance spot welding conditions for each specimen

Specimen no.	Electrode force	Welding cycle	Weld environments
1	2000 N	5 cycle	Air
2		15 cycle	
3		25 cycle	
4	2000 N	5 cycle	Controlled argon
5		15 cycle	atmosphere
6		25 cycle	
7	4000 N	5 cycle	Air
8		15 cycle	
9		25 cycle	
10	4000 N	5 cycle	Controlled argon
11		15 cycle	atmosphere
12		25 cycle	
13	6000 N	5 cycle	Air
14		15 cycle	
15		25 cycle	
16	6000 N	5 cycle	Controlled argon
17		15 cycle	atmosphere
18		25 cycle	

ical solution of 15 ml HCl, 5 ml HF and 80 ml water. Microstructures of the specimens were examined using a Nikon Epiphot 200 type optical microscope while the hardness measurements were carried out using an Instron Wolpert type Vickers hardness measurement machine under the 1 kg load.

On each specimen, three hardness measurements were made and these were averaged. The measurements were made in two directions; one along the radius of the nugget while the other along the sheet thickness (Fig. 5). Tensile shear tests were carried out on a Instron MFL type device with the tension speed of 0.5 mm/min.

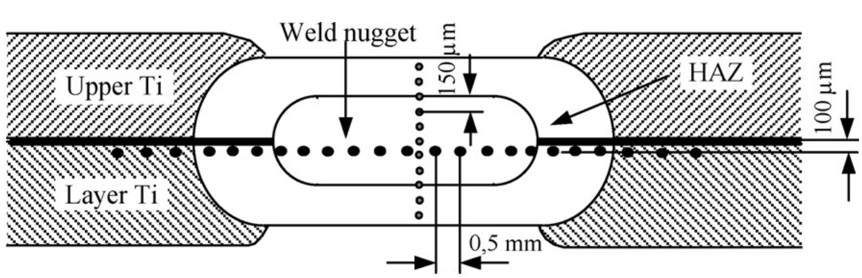

Fig. 5. Hardness measurement areas on the welded sample.

3. Results and discussion

3.1. Tensile-shearing test

A tensile-shear result obtained from the resistance spot welded specimens joined by using 5 cycles weld time is shown in Fig. 6(a). Results obtained from the resistance spot welded specimens joined by using 15 and 25 cycle weld time are shown in Fig. 6(b).

When the specimens subjected to the tensile-shearing tests were examined, the specimens welded at 5 cycles, which had lowest heat input, fractured at very low loads irrespective of the welding environment. In addition, fracture took place within the joining interface (Fig. 6(a)). In these specimens, no deformation was observed in nugget and around the heat affected zone (HAZ). These findings show that 5 cycle weld time is not enough for a good joining. However, fracture of the specimens joined at 15 cycle weld time and under 2000 and 4000 N electrode force in open air atmosphere and under controlled argon atmosphere took also place within the joining interface but cracks were observed around the nugget. Fracture of the specimens joined at 15 cycle weld time and 6000 N electrode force in open air and under argon atmosphere did not take place within the weld interface. In these specimens, fracture occurred around the nugget leaving an area like button. Similarly, the specimens joined at 25 cycle weld time under the both atmosphere conditions resulted in button like areas after the fracture and the resulting tensile shear strengths were to be higher than that of the base material. This indicates that the joining at high welding parameters is very good.

When the results of resistance spot welded specimens joined at different parameters and under different environments were examined, it is seen that welding time had the most influence on the tensile-shearing strengths of the welded joints while the welding environment had the least.

As known, the mechanical behaviour of a resistance spot weld point in conventional tensile shear test depend on the geometrical factors such as morphology of weld point, sheet thickness, etc., mechanical factors such as base metal behaviour, and also welding operations such as welding conditions, test, etc., but depend very little on metallurgical factors such as structure of weld point and the chemical composition, etc., [26].

When Fig. 6 is studied generally, it is seen that the specimens joined under the argon gas atmosphere yielded higher tensile-shearing strength results than those joined in open air. Although tensile-shearing values were most prominent in the specimens joined at low current times, increasing weld time decreased the difference in the tensile-shearing values for the both atmosphere. The results were close to each other. It can be understood from these findings that protective gas atmosphere had more pronounced effect when the weld time was low than that when the weld time was high.

3.2. Hardness measurement

Measurements were carried out on all the resistance spot welded specimens. The locations of the measurements are marked in Fig. 7. The measurement results showed that hardness values did not change considerably depending on the variations in the weld parameters. For this purpose, some of the obtained hardness values obtained from the different spot welded specimens are given Fig. 7. Fig. 7(a) gives the hardness values of the specimen welded using 15 cycle weld time and under 2000 N electrode force in open air and under argon atmosphere. These measurements were taken parallel to the interface. On the other hand, Fig. 7(b) gives the hardness values for the same specimens which were taken perpendicular to the interface. Similarly, Fig. 7(c) and (d) show the hardness values of the specimens welded under the same environment and current values but under 4000 N electrode force.

When Fig. 7 is evaluated generally, it is seen that the nugget gives the highest hardness values for all the welded joints obtained using different parameters and environments and this was followed by HAZ and weld metal. It is deduced from this finding that the applied heat input

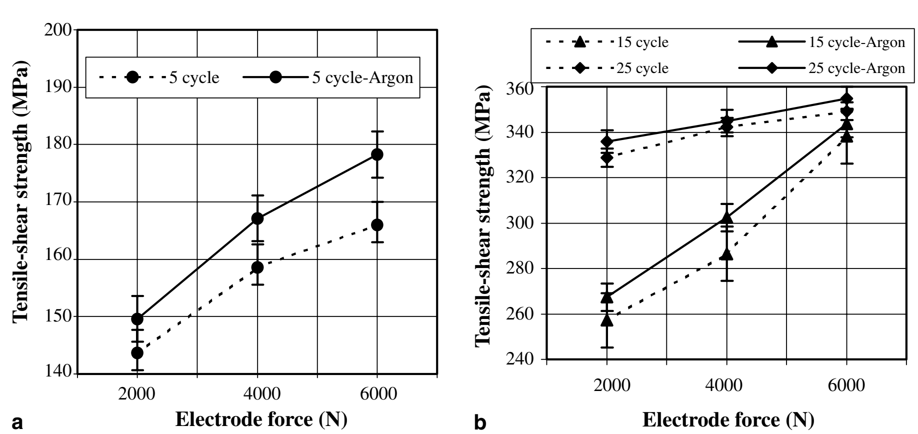

Fig. 6. Tensile-shearing test data: (a) 5 cycle weld time and (b) 15 and 25 cycle weld time.

and pressure during the welding increase the hardness of the welded zone.

In their experimental study on the resistance spot weldability of galvanised Interstital Free (cold formable) steel sheets with austenitic stainless steel sheets, Vural and Akkus [27] carried out microhardness measurements and found that the middle of the weld nugget gave the maximum hardness.

The work in this study indicates that whether the welding process is carried out in open air or under argon protection did not influence the hardness values of the joints. However, the obtained hardness values in the both measurement directions increased to some extent when the electrode force was increased and all the other parameters were kept constant. The increase of hardness is caused by the high amount of deformation at high pressures during the holding time and resting time of welding processes.

3.3. Microstructure

Fig. 8(a) shows the optical microscope image of the original CP Ti. It is seen from this image that the microstructure consists of fine equaxied α (alpha) grains. In the published literature [2], it is also stated that annealing of pure titanium at 670–700 °C is quite common and such a heat treatment causes fine equaxied α (alpha) grains in the microstructure. Fig. 8(b) shows the photograph of weld starting interface of the specimen joined using

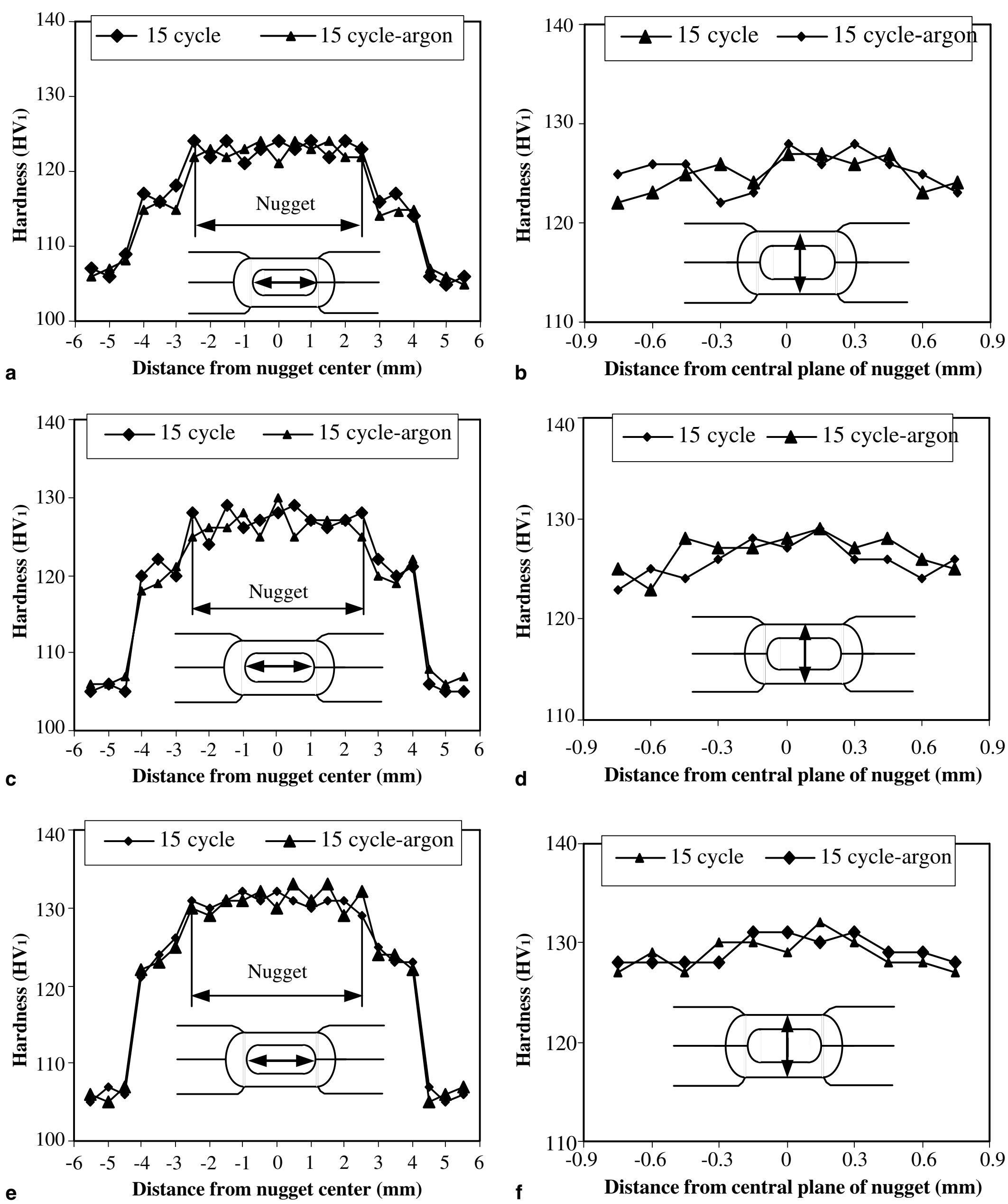

Fig. 7. Hardness of: (a) 2000 N, 15 cycle, (b) 2000 N, 15 cycle-Argon, (c) 4000 N, 15 cycle, (d) 4000 N, 15 cycle-Argon, (e) 6000 N, 15 cycle and (f) 6000 N, 15 cycle-Argon specimens welded at different parameters.

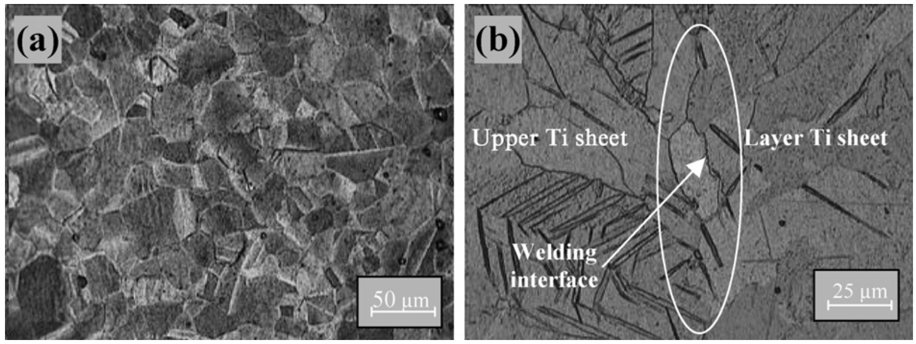

Fig. 8. Optical micrographs of: (a) base metal, (b) starting interface area of nugget joined using 2000 N pressure, 15 cycle and under argon protection.

2000 N pressure, 15 cycle and under argon protection. The zone shown by the arrow is the interface between the two materials joined and indicates that welding started from this point. It is seen that the structure of this area is quite different from the structure of the original material and the grains are oriented towards the heat centre. In addition, it is also seen that new grains were formed in the interface and these new grains are larger than the original grains due to the thermal gradient of the welding process.

Optical microscope images of the weld nugget of resistance spot welded joints are given in Fig. 9. When the images are generally evaluated, the microstructures of these areas are considerably different from those of original base metal. Unlike the base metal, it is noted that grain growth occurs due to the heat transfer and twinning occurs due to

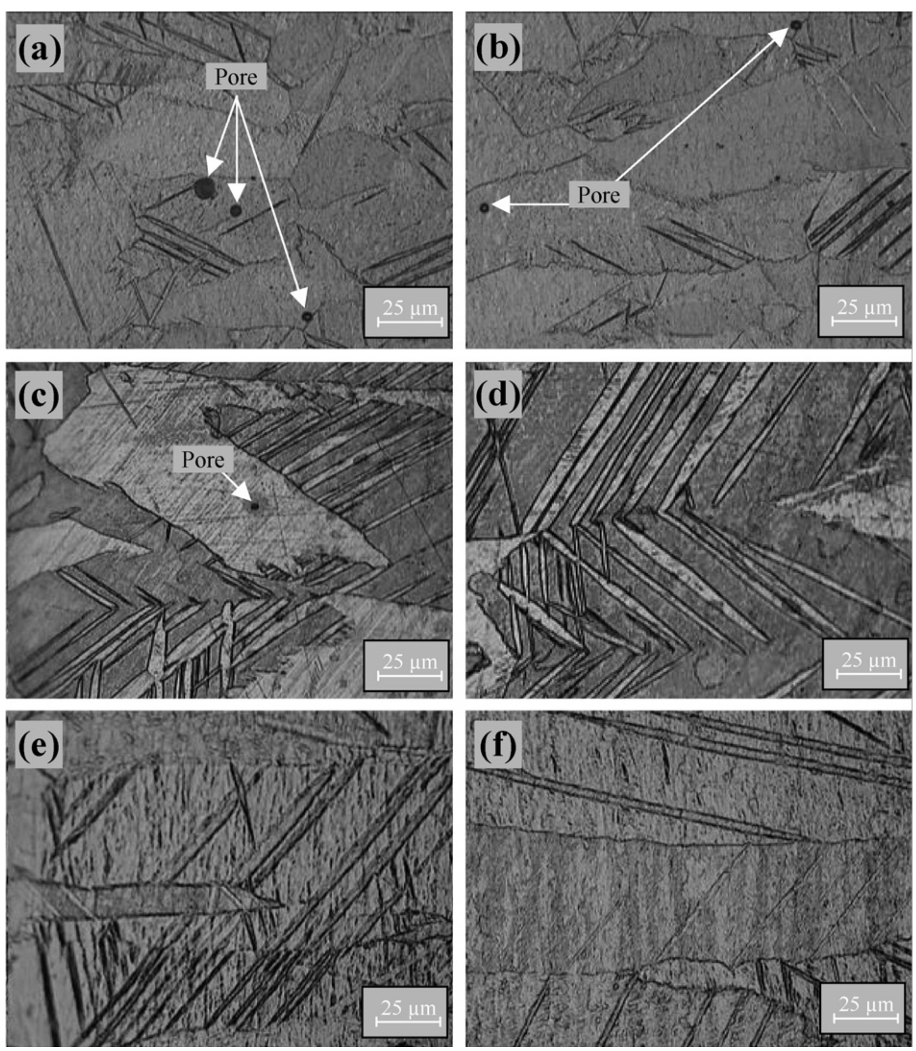

Fig. 9. Optical microscope images of the weld nugget of resistance spot welded joints joined at: (a) 2000 N, 15 cycle, (b) 2000 N, 15 cycle-Argon, (c) 4000 N, 15 cycle, (d) 4000 N, 15 cycle-Argon, (e) 6000 N, 15 cycle and (f) 6000 N, 15 cycle-Argon.

the applied pressure during the holding and resting time. Twinning in Ti materials due to the applied deformation was also reported in the literature [28]. In addition, it is clearly seen from the photographs of the resistance spot welded specimens that the formed grains were oriented parallel to the weld heat flow. The formed grains were found to be elongated parallel to the electrode compression direction and this became more evident for the specimens joined under the high electrode forces. When the photographs in Fig. 9 (especially Fig. 9(c) and (d)) are examined, it is seen that the difference in the colours of the grains is caused by the different orientations of the grain and the structure consisted of α (alpha) grains.

Fig. 9(a) and (b) give the optical microscope images of the specimen obtained using 2000 N and 15 cycle in open air and under argon atmosphere, respectively. When the images are examined, it is seen that twinning is not obvious for the both atmosphere due to the lower applied force (electrode force). In addition, pores are seen in Fig. 9(a) as this specimen was joined in open air. However, fewer pores are seen in Fig. 9(b) as this specimen was joined under argon atmosphere. These results indicate that the use of argon during the welding process protects the welding zone from detrimental influences of the atmosphere and therefore results in a good bonding.

Fig. 9(c) and (d) give the optical microscope images of the specimen obtained using 4000 N and 15 cycle with and without protective atmospheres, respectively. When these specimens are compared to those obtained under 2000 N applied load, it is seen that the amount and dimensions of the twinning increase, however, the pores in the nugget decrease and/or are eliminated. Another important difference seen from these images are the larger grain sizes obtained under 4000 N although the weld times were the same for the both applied load. This results in expansion of the nugget depending on the increasing electrode force during the welding.

Tang et al. [29] found that increasing welding time also increased heat input when other conditions were kept constant, but only linearly. Compared with weld current effect, therefore the workpiece softened less and the force change took longer. The force constrains the thermal expansion of the nugget volume. When a large force is applied, the thermal expansion suffers from a stronger constraint and creates a larger reaction force. Therefore, larger force change is expected.

Fig. 9(e) and (f) give the optical microscope images of the specimens obtained using 6000 N and 15 cycle with and without protective atmospheres, respectively. When the both images are examined, no tracks of pores that were seen on the specimens joined at lower pressure are observed due to the high pressure applied. Nonetheless, when compared to the welds obtained using the same current time and under 2000 and 4000 N pressure, grain growth in these specimens increased due to high heat input. Due to the applied deformation the size of twin lines increased more.

As known [30], the pressure on the electrodes in maintained for a hold or forging time while the weld solidifies during the performance of resistance spot welding. When the current is switched off (automatically) the weld solidifies under pressure.

During this period, stress hardening takes place in the welding zone as the pressure on the material acts on the weld due to the rapid cooling of weld material. Increasing current time and electrode force increases deformation hardening and this increase, in turn, increases twinning in the weld zone. Ayman et al. [31] reported that the sudden increase of strain hardening rates seen after small strains in titanium correlate with the onset of deformation twinning. This result appears to match quantitatively with Hall–Petch grain size strengthening.

4. Conclusion

(i) Increasing welding time and electrode force increased tensile-shearing strength of the resistance spot welded specimens.
(ii) The welds carried out under argon gas atmosphere yielded better tensile-shearing strength than those effected in open air.
(iii) Among the all parameters, the welding time had the most influence on the tensile-shearing strength of the welded specimens while the welding environment had the least influence.
(iv) The weld nugget gave the highest hardness values, and this was followed by HAZ and weld metal.
(v) It was seen that argon gas used during the welding process did not change the hardness values in the joining zones.
(vi) Microstructural examination showed that deformation during the welding process was in the form of twinning rather than shearing in the welding zone. It was also observed that high pressure and welding time increased the twinning.

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