Effect of welding parameters on the properties of the Ti-6Al-4V plate resistance spot weld joint

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Abstract. Titanium alloy Ti-6Al-4V properties advantage gives it a well-known reputation for decades as a reliably material used in a wide range and specific application of resistance spot welded joint such as automotive & aviation products. High strength joint is created depends on the welding parameters used in resistance spot welding. Particular problems occurred about the effect of welding parameters on pure titanium and titanium alloy mechanical and physical properties from previous researches. Some pores and acicular α' phase appeared in the microstructure, which caused partial interfacial failure mode in the tensile testing. This study is conducted to study the influence of welding parameters for Ti-6Al-4V weld nugget mechanical and physical properties and discover its optimum level of parameters. Tensile-shear testing is used to observed the optimum level. In the optimum level microstructure result reveals that in the weld nugget zone as a fusion zone the lamellar α+β is dominantly observed, this contrasts sharply with the base metal and the heat-affected zone where the primary α and β phase appear to be more dominant. The highest hardness value is discovered in the weld nugget area near the center proving the contribution of the lamellar α+β on this area.

1. Introduction

Resistance spot welding is one of the very effective welding method used for thin or thick metal sheets. It has a quick time of welding and also having a good quality of strength at the joint. Titanium alloy is one of the widely used materials in industrial needs, particularly in the automotive and aerospace industries [1].

In resistance spot welding, the weld joint is generated by the heat which is combined with pressure from the electrode and at a certain welding time. The name of resistance spot welding comes from the fact that the weld is not only influenced by the weld current, pressure, and time but also the material resistivity to the current flow as well, which causes a localized heating area in the material [1]. One of the best materials that had been used for so many years for industrial applications and welded using resistance spot welding (RSW) is Titanium alloy especially Ti-6Al-4V, for example in the automotive...
industry. Titanium alloy grade 5 or Ti-6Al-4V has 130 Ksi or 895 MPa of tensile strength with 120 Ksi or 828 MPa of Yield Strength making it one of the strongest alloys among others [2-4].

Titanium has low density leading to deform easily during resistance spot welding with high force, but in another way it has a high melting point [5], so it must be investigated the optimum parameter that can be applied on its resistance spot welding. A previous study has been done with the same metal combination but with 1 mm of thickness and provides the maximum tensile-shear load of 14.3 kN [6]. Titanium alloys prove to be one of the greatest corrosion-resistant metal by creating a thin, but sufficient to protect its body as a surface oxide film. This film, which is primarily TiO2, is highly persistent, supportive, chemically stable, and can spontaneously and instantaneously recover itself if mechanically damaged [7].

Several types of research conducted a study about the effect resistance spot welding parameters on pure titanium and titanium alloy properties [6][8]. The results concluded that the changing of parameters did affect the impact on its properties. But some problems occurred, in the microstructure formed acicular α' phase [6] and appeared several pores [8], those caused partial interfacial failure mode in the weld joint tensile result. This study's objectives are to study the influence of welding parameters for titanium alloy resistance spot weld nugget mechanical and physical properties, and also to discover the optimum level of its selected parameters.

2. Experimental procedure

In this study, two-piece plates of titanium alloy (ASTM grade 5) with 3 mm of thickness were used to be welded together under resistance spot welding. The dimension of each sample was determined referred to ASTM D1002 standard and under the lap joint configuration during resistance spot welding [9]. The experiment was conducted using data acquired in our labs. The appearance of the resistance spot welding diagram and the sample can be seen in figure 1. In figure 1 (a) it can be seen that both of the material plates are pinched by the electrode tips from a different direction. The electrode tips are given force and the current flows through it to the materials and generating heat. The welding time is applied to give the heat to steadily melting down the materials and join it together forming a fusion zone called weld nugget. figure 1 (a) & (b) shown that the weld nugget shape is rounded following the shape of the electrode tips cross-sectional area. The welding experiment is performed under room temperature or normal atmospheric conditions and based on AWS D8-9M:2012 standard [10]. The chemical composition of titanium alloy (ASTM grade 5) is presented in table 1 [4].

![Resistance spot welding diagram](image1)

![Sample top view](image2)

![Sample right view](image3)

**Figure 1.** (a) Resistance spot welding diagram, (b) sample top view, (c) sample right view.
Table 1. Chemical composition of titanium alloy ti-6al-4v (ASTM grade 5) [4].

| Element       | Titanium alloy grade 5 |
|---------------|------------------------|
| Nitrogen, max | 0.05                   |
| Carbon, max   | 0.08                   |
| Hydrogen, max | 0.015                  |
| Iron, Max     | 0.40                   |
| Oxygen, max   | 0.20                   |
| Aluminum      | 5.5-6.5                |
| Vanadium      | 3.5-4.5                |
| Titanium      | Balance                |

The welding parameters set up could be selected manually on the welding machine control panel for the current and welding time, while the force can be set from its pressure controller. Three current parameters are selected and varied, which are: 8, 9, and 10 kA. While the others are kept constant, such as 35 cycles of squeeze time, 30 cycles of welding time, 15 cycles of holding time, 0 cycle of off time, and 4 kN of electrode force. From the three varied current parameters, the tensile test result will show which one having the highest value. Thus, the sample with the selected parameter will be analyzed for its microstructure and hardness testing.

The maximum tensile-shear stress of the samples is defined using tensile testing referred to as ASTM E8/E8M-13a standard [11]. Microstructure analysis for the selected parameter using micro etching and optical microscope referred to the ASTM E407-07 standard [12]. Hardness distribution test using Vickers micro-hardness referred to ASTM E92-17 standard [13].

The Zwick/Roell Universal Tensil Machine which has 20 mm/min of ramp speed at room temperature and 50 kN of maximum load is utilized to conduct the tensile-shear testing. The microstructure observation is conducted in the cross-sectional area of the weld nugget with etching activities using Keller's reagents and optical observation using a LEICA optical microscope made in Germany. The hardness distribution is observed for the similar weld nugget cross-sectional area to test the hardness value using Vickers microhardness under the indentation load of 200 gf to obtain a hardness profile.

3. Result and discussion

3.1. Resistance spot welding result and tensile testing
The welding result shows a very good shape of the weld nugget. As can be seen in figure 2 the weld nuggets are perfectly circular with their fusion zone in the center and thin heat affected zone at its edge for the three samples as well. Each parameter produced different nugget diameters among each other and this can be seen in Table II. To determine the electrode diameter which will be used, it is required to calculate based on the standard that: \( d > 4\sqrt{t} \), where \( t \) describes the sheet/plate thickness [14]. Hence, since this study uses 3 mm of titanium alloy Ti-6Al-4V plate, the electrode diameter should be calculated as \( d > 6.9 \) mm. Table 2 shows the measurement of weld diameter by calculating the average diameter of six different measurements from each sample to get the proper measurement result and also indentation.
depth. As can be seen in table 2 that with the constant parameter of welding time and force, the more increase of welding current the more increase weld nugget diameter. The increase of current also increasing the heat generated by the welding electrodes hit to the material. Thus, increasing the weld temperature in the material, causing a much larger weld diameter. As well as the indentation depth, because the increase of the weld temperature also increasing the material ductility during welding, so the giving electrodes penetration much deeper.

![Figure 2](image-url)

Figure 2. Weld nugget result at welding current respectively: (a) 8 kA, (b) 9 kA, (c) 10 kA.

The resistance spot welding result quality is generally implied by the weld nugget strength. Different amounts of welding parameters such as welding current will lead to a different result of weld nugget [16-31]. Tensile testing is the most commonly used to evaluate the mechanical properties in a static condition. Physical properties also could be determined by evaluating the fracture mechanism of the tensile test. According to the tensile testing result, table 2 shows that the increase of weld nugget diameter and indentation depth is not followed by the tensile stress. It is increased from 8 kA to 9 kA, but in 10 kA it is decreased, because the deeper indentation depth creating a thinner fusion zone, thus also weakening its strength.

Table 2. Weld nugget physical properties and tensile stress.

| Exp. | Current (kA) | Welding time (cycle) | Welding force (kN) | Weld nugget diameter (mm) | Indentation depth (mm) | Max. tensile stress (MPa) |
|------|-------------|----------------------|-------------------|--------------------------|-----------------------|--------------------------|
| 1    | 8           | 30                   | 4                 | 10.763                   | 0.365                 | 483.048                  |
| 2    | 9           | 30                   | 4                 | 12.147                   | 0.380                 | 521.801                  |
| 3    | 10          | 30                   | 4                 | 12.853                   | 0.465                 | 485.604                  |

According to the tensile testing result, it shows that the failure modes of the welded joint are an interfacial failure for both three samples. The failure mode tends to brittle failure. It is shown in figure 3 that in welding current 8 kA, the failure occurs mostly in the weld nugget edge seems that the weld nugget is more brittle than in the HAZ and base metal. It is different in the welding current of 9 kA, the failure is occurred in outside the nugget area, mostly in the base metal. The opposite result occurs in 10 kA welding current, the failure is turned back in the nugget area mostly, meaning that the nugget zone turned weakened due to the thinner indentation depth caused by higher heat generated by higher current flow through the welding electrodes.
As observed in figure 3, the type of failure for the whole samples are cup and cone which are usually appeared in the failure of ductile metal. As the tensile stress in the sample approaches its yield strength, due to the sample type is a lap joint with its weld joint in both meeting endpoint, the sample is started to bend each other as can be seen in figure 4. The bending is caused as the weld joint holds the shear stress from both sides. As the load continues increasing, small cavities are formed at the bent portion of the material. The further increase of load causes the cavities to gain bigger and eventually coalesce to form an elliptical crack perpendicular to the stress direction. Eventually, the material fails, and the fractured at both materials ends to create the distinctive cup and cone shape. The failure point is the representation of the weakest area around the weld nugget zone whether it is in the weld nugget, HAZ or base metal.

3.2. Microstructure analysis
In resistance spot welding, the effect of the heat input created by the welding parameters greatly affects the microstructure changes in the weld nuggets. Fusion zone (FZ), heat affected zone (HAZ), and base metal (BM) will provide different types of microstructure that will lead to mechanical performance [15].
The optical microscope is used to identify the microstructure and physical properties of the selected welded joint from the previous tensile test, which is welded under 9 kA of welding current, 30 cycles of welding time, and 4 kN of welding force, and the result can be seen in figure 5.

Figure 5. Microstructure analysis at 9 kA of welding current, 30 cycles of welding time, and 4 kN of welding force: (a) base metal; (b) heat-affected zone (HAZ); (c) weld nugget zone.
Titanium alloy Ti-6Al-4V consists of two crystallographic forms which are α which has a hexagonal close-packed (hcp) crystal structure & β phase which has a body-centered cubic (bcc) structure. Even though this particular alloy is relatively hard to form even when it is annealed, α + β alloys commonly have good formability [6]. The microstructure observation is conducted for the cross-sectional area of the welded joint perpendicular to the weld surface and mounted in a dried epoxy followed by grinding and polishing in a thorough sequence. Then, the cross-section sample is etched using the etching solution of Keller’s Etch.

It is observed that the primary α phase is often represented by the bright color and the β phase is clearly shown in a dark color. Since the microstructures of the sample determined on the cross-sectional area of the weld joint as can be seen in figure 5, there are seems to be a difference in the weld nugget, HAZ, and also in the base metal. As shown in figure 5 (a) the microstructure of the base metal consists of primary α phase (colored in white) and β phase (colored in black) but in the Heat Affected Zone (HAZ) as shown in figure 5 (b), it is stated to be formed slightly of the lamellar α+β so the microstructure consists of primary α, β phase, and lamellar α+β. But in the weld nugget zone shown in figure 5 (c), as a fusion zone the lamellar α+β starting to dominantly showing themselves combine with primary α. In titanium alloy, the phase transformation is much affected by the temperature and the cooling rate. In figure 5 (c) the microstructure is called duplex because the discontinuous equiaxed α distribute less than 50% in the transformed matrix β. This microstructure is obtained in the high temperature of the α+β phase zone which can contribute to the wide range of optimum mechanical properties [32].

The cooling rate also greatly affects the changes in the alpha and beta phases. When resistance spot welding occurs at room temperature, the cooling rate is sequential from slowly in the middle of the weld nugget as the center of the heat input, to the heat-affected zone (HAZ) and base metal which are located far from the center of the heat input, so that they have a faster cooling rate. Increasing the cooling rate causes smoother on the microstructure. The rapid cooling rate will cause the growth of phase boundaries both alpha and beta to grow perpendicular to the lamellar and appear nucleated [32]. So that it does not form many new lamellar on the microstructure, especially on the base metal. The thin section in the heat-affected zone which is close enough to the fusion zone causes this area to start to accommodate the new lamellar that has formed due to the reduced cooling rate. In contrast to weld nuggets, the high fusion zone temperature as the main area of heat input and slow cooling rate provides ample opportunity for the formation of new lamellar from the alpha and beta phases. The form of lamellar shown in figure 5 increasing the weld nugget zone hardness and strength. The more lamellar structure is formed thus increasing the more hardness and strength.

3.3. Hardness testing
The application of hardness distribution testing is to indicate metal wear-resistant. The harder the metal area the more wear-resistant. Since the microstructure of the three areas is different from each other (infusion zone, HAZ, and base metal) the hardness distribution should be tested to prove that its hardness value different from each other or not. This test was using the micro-hardness Vickers test with 200 gf of load on 20 indentation points along the cross-section of the welded joint. Figure 6 is showing the hardness test positions on the cross-sectional sample, 19 points were tested across the cross-sectional area. Each point has 0.8 mm on the base metal and HAZ, and 1.5 mm on the weld nugget zone, due to the limited size of mounting.
The result of hardness testing can be seen in figure 7 & table 3. The result of the lowest HV is in the base metal with the value of 219.4, meanwhile, in the HAZ the HV is raising because the lamellar α+β slightly formed increasing the hardness of the material. Approaching the weld nugget zone as the fusion zone the HV is increasing until the peak of the hardness is nearly the center of the weld nugget, making the weld nugget is the hardest zone of all. The highest HV is 470.9, in the weld nugget area near the center. It is proving the result of microstructure in figure 5 which shows that in the fusion zone is observed the lamellar α+β phase dominantly appeared increasing the hardness and ductility.

![Figure 6. Hardness testing positions in the weld nugget.](image)

![Figure 7. Hardness distribution chart.](image)
Table 3. The result of Vickers microhardness measurement.

| No | Position | D1  | D2  | HV  |
|----|----------|-----|-----|-----|
| 1  | -10      | 35.05 | 33.2 | 318.5 |
| 2  | -9.2     | 36.32 | 34.36 | 297   |
| 3  | -8.4     | 33.64 | 32.82 | 335.9 |
| 4  | -7.6     | 34.52 | 30.33 | 352.8 |
| 5  | -6.8     | 33.74 | 33.74 | 320.3 |
| 6  | -6       | 31.54 | 30.82 | 381.4 |
| 7  | -4.5     | 30.03 | 30.37 | 406.6 |
| 8  | -3       | 29.46 | 29.98 | 419.9 |
| 9  | -1.5     | 29.49 | 29.52 | 426   |
| 10 | 0        | 28.56 | 29.03 | 447.3 |
| 11 | 1.5      | 28.56 | 27.57 | 470.9 |
| 12 | 3        | 32.16 | 31.68 | 364   |
| 13 | 4.5      | 32.45 | 32.38 | 353   |
| 14 | 6        | 32.91 | 33.6  | 335.4 |
| 15 | 6.8      | 34.39 | 34.18 | 315.5 |
| 16 | 7.6      | 34.67 | 34.67 | 313.4 |
| 17 | 8.4      | 34.04 | 33.42 | 326   |
| 18 | 9.2      | 35.9  | 35.91 | 287.7 |
| 19 | 10       | 35.89 | 35.46 | 291.4 |

4. Conclusion
The weld joint maximum stress from the tensile testing for welding parameters of 8 kA, 9 kA & 10 kA are respectively: 483.048 MPa, 521.801 MPa, 485.604 MPa. Then the weld joint with the welding parameters of 9 kA current, 30 cycle welding time & 4 kN force which produce 521.801 MPa maximum stress, is selected to be the strongest weld joint among others from the tensile testing result. Meanwhile, the pull-out failure with cup and cone shape is the mostly failure mode that appeared in samples and broken mostly around the HAZ and base metal area, meaning that the weld nugget is stronger than the HAZ and the base metal. The Primary $\alpha$, $\beta$ phase, and lamellar $\alpha+\beta$ are the microstructures that appeared in the weld nugget zone. Particularly the form of lamellar $\alpha+\beta$ making the weld nugget stronger and harder than the HAZ and the base metal. For the result of the hardness test, the highest HV is 470.9, in the weld nugget area near the center. It explains that the increase of the welding parameter particularly current will increase the weld nugget strength. But when the current is increased, the strength will be reduced because of the thinner indentation depth formed. It is caused by higher heat generated by higher current flow through the welding electrodes.
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