Tensile Deformation Behavior of Ultrasonically Consolidated Laminated Ti-Al Composites at Warm Forming Temperatures

İrfan Kaya*

Department of Mechanical Engineering, Faculty of Engineering, Eskisehir Technical University, Eskisehir, Turkey
*irfan_kaya@eskisehir.edu.tr

Received: 26 September 2018
Accepted: 06 November 2018
DOI: 10.18466/cbayarfbe.464135

Abstract

The objective of the present study is to characterize the mechanical behavior of laminated metal composites (LMCs) that consist of commercially pure titanium and 1100 aluminum layers which were ultrasonically consolidated. Ultrasonic consolidation is a low temperature process used to fabricate layered solid metal structures. Tensile tests of Ti-Al laminated composites (in 3, 5, and 7 bilayer configurations) were performed at four various temperatures (25 ºC, 100 ºC, 200 ºC, and 300 ºC) using strain rate of 0.017 /s. The effect of temperature, sonotrode travel direction, and number of layers on the material behavior were discussed on the basis of uniaxial tensile test results. The ultimate tensile strength and yield strength is found to decrease with increasing temperature. In general, high strain values were obtained in Y samples compared to X samples. The maximum strain value was 0.42 at 300 °C temperature in the 5 bilayer Y sample.

Keywords: Laminated metal composites, ultrasonic consolidation, Ti-Al composites, ultrasonic welding, mechanical characterization, warm forming.

1. Introduction

In recent years, scientists have been extensively investigating composite materials instead of traditional materials due to their advantages such as less weight, more strength, and lower cost [1].

Laminated metal composites have gained popularity due to a good combination of ductility, strength and density [2, 3]. LMCs have been fabricated by a variety of techniques, the most common of which are roll bonding, coextrusion, and ultrasonic welding. The ultrasonic consolidation (UC) method can be applied to combine most commercially available metals such as aluminium, titanium, magnesium, copper and steel [4].

Ultrasonic consolidation, a low temperature solid state additive manufacturing process, is one of the new methods used to produce laminated metal composites [5-7]. During this process, illustrated in Figure 1, ultrasonic energy is applied to the workpieces under a low compressive load (Normal force). The ultrasonic vibrations which are generated by ultrasonic transducers produce a friction that breaks up oxide film and contaminant on the surface allow good metal-to-metal contact. The compressive load applied to the workpieces permits the clean metal surfaces to stick together and thus the two components are joined together [8, 9].

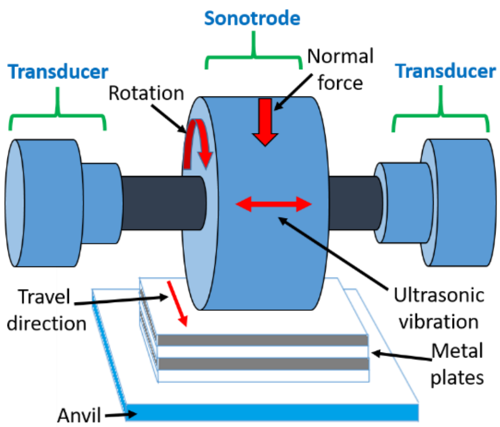

Figure 1. Schematic of the ultrasonic consolidation process.

The UC process works at temperatures much lower than the melting temperature of raw materials and enables to weld dissimilar materials [10]. Compared to other welding methods for metals, applied to low temperature and low compressive load makes this process attractive for fragile structures and heat sensitive metals to be consolidated. The low temperature ultrasonic consolidation technology has been used for welding of wide variety of dissimilar metals including Ti-Al LMCs [11, 12] and Al-Steel [13] to prevent the formation of detrimental intermetallic. In addition, thermally sensitive and damage intolerant fibers such as shape memory alloys (SMAs) and optical fibers can be embedded between the metallic foils by using a UC process [14, 15].

Since the Al is light and Ti has high strength property, an examination of laminated Ti-Al composite is of great importance for applications in the automotive and aerospace industries [16, 17]. Ultrasonically consolidated Al 1100- CP Ti laminated metal composite was investigated for armor applications due to their high strength and toughness properties by Sano et al. [18]. They reported that the CP-Ti/TiAl3/Al laminate had a higher spall strength compared to CP-Ti/Al laminate. Wolcott et al. [10] investigated the mechanical behavior of ultrasonically consolidated as-built and post-process heat treated Al 1100 / CP Ti composite samples. They found that heat treated samples showed significant increases in mechanical strength as compared to as-built samples.

In our previous work on Ti-Al LMCs, Ti- Al laminates were built onto a 1.527-mm-thick aluminum substrate by means of UC with different number of layer configurations were studied [19]. In the current study, Ti- Al LMCs without the thick aluminum substrate were tested under 0.017 /s strain rate.

2. Materials and Methods

The laminated metal composites were fabricated via ultrasonic consolidation method using titanium (Ti) and aluminum (Al 1100) plates. In this study, Ti refers to commercial pure Ti throughout this paper. The density of titanium and aluminum are; 4.5 g/cm^3 and 2.7 g/cm^3, respectively. The chemical compositions of metals that are used in the composite are shown in Table 1. The thickness of each layer is 0.127 mm. The laminate is built up on a Ti substrate by rolling over each Ti-Al foil with a sonotrode that produces ultrasonic vibration with low energy consumption (Figure 2). Three different numbers of bilayer (in 3, 5, and 7 bilayer configurations) were tested.

Table 1. Chemical composition of Al and Ti.

Aluminum 1100		Commercial Pure Titanium	
Iron	0.95	Carbon	0.002
Copper	0.05-0.2	Titanium	99.9221
Manganese	0.05	Iron	0.03
Zinc	0.10	Nitrogen	0.004
EA	0.05	Hydrogen	0.0019
Aluminum	99.00	*	*

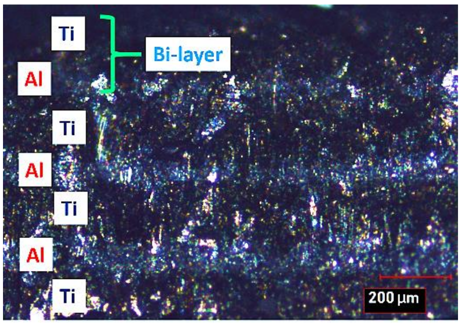

Figure 2. Ti-Al laminated composite (3 bilayer sample).

The dimensions of tensile coupons are given in Figure 3. The tensile coupons were prepared in two directions: (1) sonotrode travel direction is perpendicular to the pulling direction (named X), and (2) sonotrode travel direction is parallel to pulling direction (named Y) (Figure 3). The 3, 5, and 7 bi-layers with thickness of 0.889, 1.397 and 1.905, respectively, were used for tensile test.

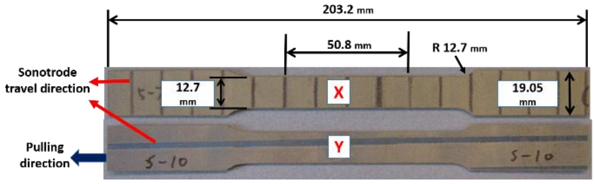

Figure 3. Dimensions of the tensile test samples.

A 10 kN electromechanical MTS tensile testing machine equipped with a furnace was used for testing the mechanical properties of laminated metal composite materials (Figure 4). The specimens were held by the grippers. The temperature of the sample was measured with K-type thermocouple attached at the center of the sample. Ti-Al LMC coupons were drawn to the single axis at a constant speed and at a constant temperature on the warm tensile test device. For each testing condition, three specimens were used to ensure the repeatability of the results.

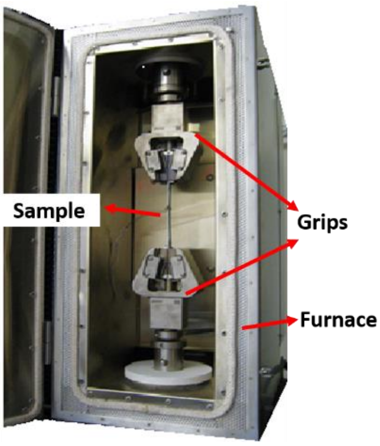

Figure 4. Tensile testing machine equipped with a furnace.

3. Results and Discussion

Figure 5 shows the tensile stress-strain responses of laminated metal composites in different directions (X and Y) at selected test temperatures. Figure 5(a) through (c) show the tensile test results for X samples while Figure 5(d) through (f) show the results of Y samples. The test coupons were loaded at four test temperatures (25 ºC, 100 ºC, 200 ºC, and 300 ºC) at a strain rate of 0.017 /s. The flow stress initially increases linearly with increasing strain up to the yield strength (YS). This linear section is not included in the graphs. Then, flow stress continues to increase non-linearly with increasing strain up to ultimate tensile strength (UTS) which the last stress level is shown in Figure 5. The YS and UTS are significant factors to characterize the material properties.

In Figure 5, it is seen that the ductility increased slightly with the temperature. The strain values were 0.24, 0.25, 0.31, and 0.32 at 25 °C, 100 °C, 200 °C, and 300 °C, respectively, for 3 bilayer X sample (Figure 5(a)). The strain values were 0.26, 0.3, 0.35, and 0.35 at 25 °C, 100 °C, 200 °C, and 300 °C, respectively, for 3 bilayer Y sample (Figure 5(d)). In 5 bilayer X sample, the strain value was 0.25 at 25 °C and increased to 0.40 at 300 °C (Figure 5(b)). These values were 0.28 and 0.42 at 25 °C and 300 °C, respectively, for 5 bilayer Y sample (Figure 5(e)). The strain values were 0.28 and 0.41 at test temperature of 25 °C and 300 °C, respectively, for 7 bilayer X sample (Figure 5(c)). The strain values of 7 bilayer Y samples were 0.26 and 0.37 at 25 °C and 300 °C, respectively (Figure 5(f)).

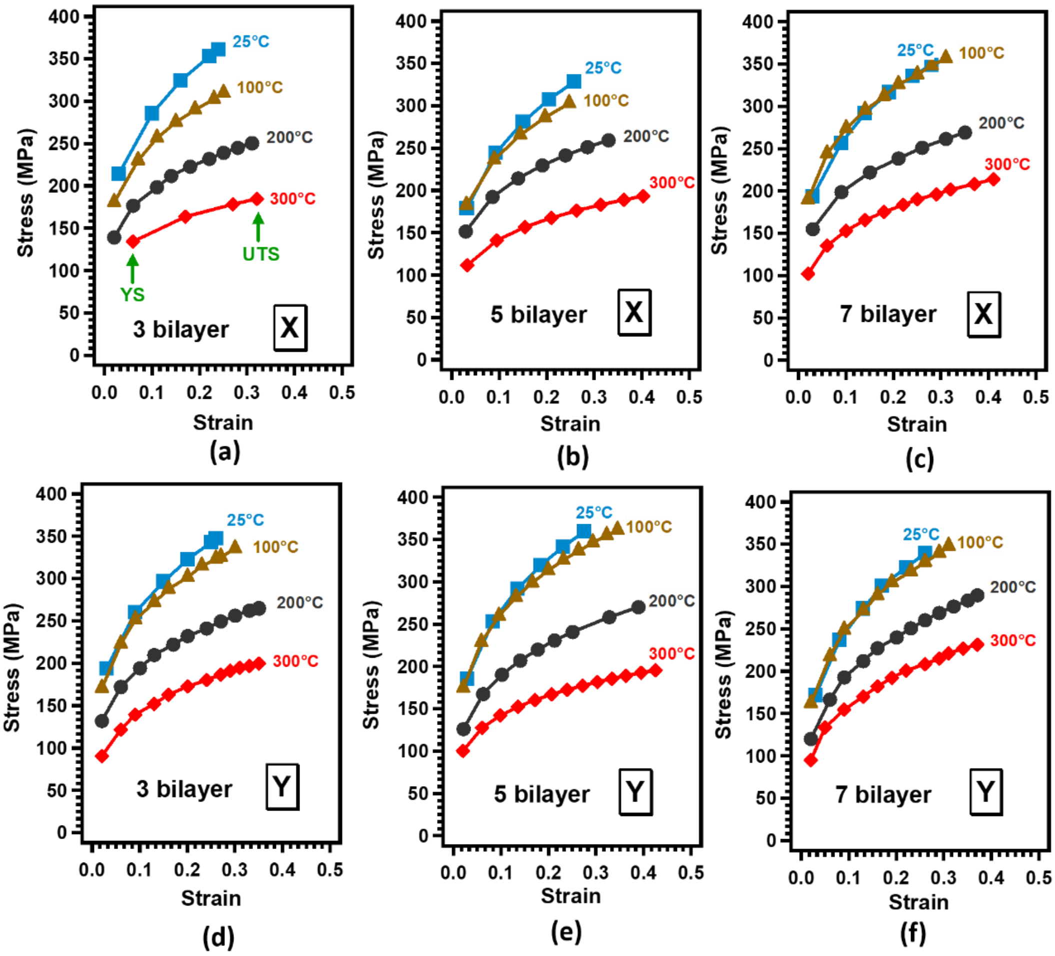

Figure 5 Stress-strain curves of laminated metal composites obtained from tensile tests; (a to c) X samples, and (d to f) Y samples.

Figure 6 shows the UTS, YS, and strain as a function of the number of bilayer along the X and Y samples at four test temperatures. UTS, YS, and strain were extracted from Figure 5 and plotted in Figure 6.

As shown in Figure 6 (a) and Figure 6 (b), the UTS and YS both decrease with increasing test temperature. In the 3 bilayer X sample, increasing the temperature from 25 °C to 300 °C decreased the UTS value from 361 MPa to 185 MPa and increased the strain value from 0.24 to 0.32. The stress was reduced by almost half with the temperature increased. The decrease in the UTS with increasing test temperature (from 25 °C to 300 °C) is greatest for the 3 bilayer X sample (176 MPa) and least for the 7 bilayer Y sample (107 MPa). The decrease in the YS with increasing test temperature (from 25 °C to 300 °C) is greatest for the 3 bilayer Y sample (103 MPa) and least for 5 bilayer X sample (67 MPa). Examining the results in Figure 6(a) through (c), it is seen that UTS did not significantly change with increasing number of bi-layers for both X and Y samples above the 100 °C test temperature. The UTS values were 251 MPa, 259 MPa, and 269 MPa for 3 bilayer, 5 bilayer, and 7 bilayer samples, respectively, at 200 °C test temperature for X samples, while these values were 265 MPa, 270 MPa, and 289 MPa for 3 bilayer, 5 bilayer, and 7 bilayer at test temperature of 200 °C, respectively, for Y samples.

In general, higher YS values were obtained in the X samples than in the Y samples. In X samples, the YS values were 139 MPa, 152 MPa, and 155 MPa for 3 bilayer, 5 bilayer, and 7 bilayer, respectively, at 200 °C test temperature. In Y samples, the YS values were 132 MPa, 126 MPa, and 120 MPa for 3 bilayer, 5 bilayer, and 7 bilayer, respectively, at 200 °C test temperature.

The difference between UTS and YS decreases with increasing test temperatures. The small difference means high YS/UTS ratio. Especially YS/UTS value is very high for the 3 bilayer sample at 300 °C compared to other samples. The detection of initial signs of failure becomes difficult compared to other conditions.

In Figure 6 (c), it is seen that the strain values of Y samples were higher than the strain values of X samples. In 3 bilayer and 5 bilayer, Y samples exhibited greater elongation than the X samples at all temperatures. However, looking at the results for the 7 bilayer, the elongation values for X and Y samples are close to each other at all temperatures, except 300 °C. It was 0.28 and 0.26 at 25 °C and 0.31 and 0.31 at 100 °C and 0.35 and 0.37 at 200 °C along the X and Y samples, respectively.

In the X samples, elongation increased with increasing number of bilayer. Strains were 0.24, 0.25, and 0.28 at 25 °C and 0.32, 0.4, and 0.41 at 300 °C along the 3, 5, and 7 bilayer samples, respectively. This increase did not appear in the Y samples.

In general, the enhanced elongation becomes significant at 200 °C. The strain values of 3 bilayer and 5 bilayer were 0.31 and 0.33 at 200 °C, respectively, for X samples. At the same test temperature, the strain values of 3 and 5 bilayers were 0.35 and 0.39, respectively, for Y specimens.

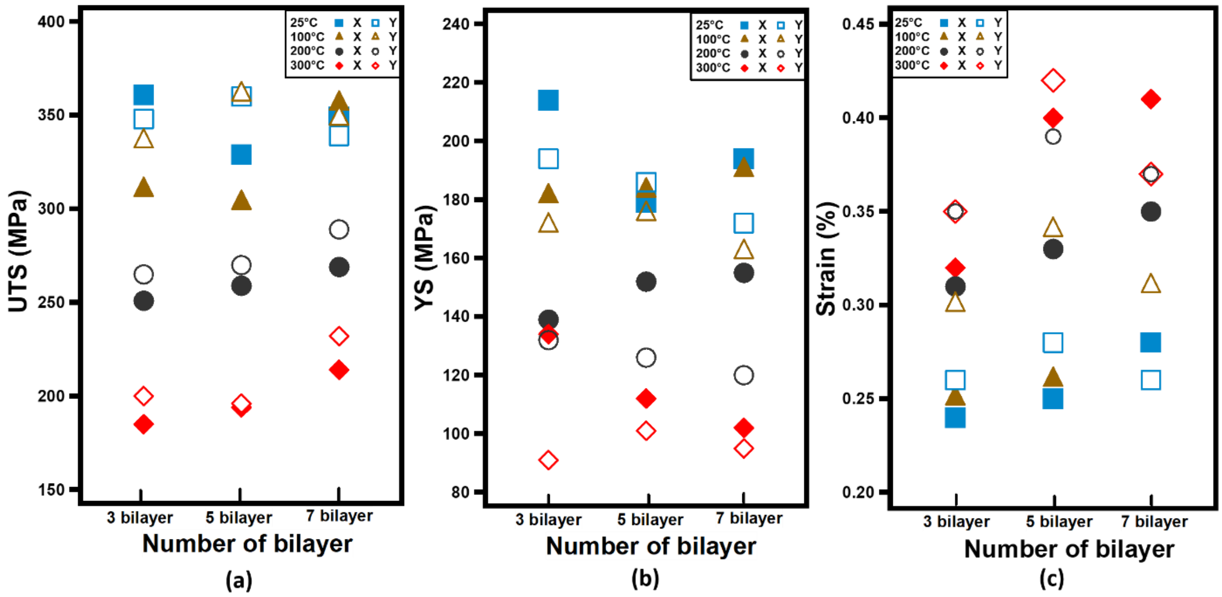

Figure 6 Stress-strain curves of laminated metal composites obtained from tensile tests; (a to c) X samples, and (d to f) Y samples.

Table 2. UTS, YS and strain values of laminated metal composites.

	3 bilayer						**5** bilayer						**7** bilayer					
	X			**Y**			**X**			**Y**			**X**			**Y**		
Temp. (°C)	**UTS (MPa)**	**YS (MPa)**	**Strain (%)**	**UTS (MPa)**	**YS (MPa)**	**Strain (%)**	**UTS (MPa)**	**YS (MPa)**	**Strain (%)**	**UTS (MPa)**	**YS (MPa)**	**Strain (%)**	**UTS (MPa)**	**YS (MPa)**	**Strain (%)**	**UTS (MPa)**	**YS (MPa)**	**Strain (%)**
25	361	214	0.24	348	194	0.26	329	179	0.25	360	186	0.28	349	194	0.28	339	172	0.26
100	310	181	0.25	336	171	0.3	303	183	0.26	361	175	0.34	356	190	0.31	348	162	0.31
200	251	139	0.31	265	132	0.35	259	152	0.33	270	126	0.39	269	155	0.35	289	120	0.37
300	185	134	0.32	200	91	0.35	194	112	0.4	196	101	0.42	214	102	0.41	232	95	0.37

According to the results shown in Table 2, within all materials, 5 bilayer Y sample showed maximum elongation. The maximum strain value was 0.42 at 300 °C test temperature at 0.017 /s strain rate for 5 bilayer sample (Figure 6(c)). The effect of the test temperature on the elongation was observed in at most 5 bilayers. Strain values increased by about 0.15 for 5 bilayer X and Y samples. According to Figure 6(c), the highest strain value of 0.35 was reached at 200 °C and 300 °C test temperatures for Y sample while the highest value was 0.32 for X sample at 300 °C in 3 bilayer samples.

4. Conclusion

This paper has made an attempt to study the tensile behavior of ultrasonically consolidated Ti-Al composites (3, 5 and 7 bilayers) at four different temperatures (25 °C, 100 °C, 200 °C, and 300 °C). The conclusions drawn from the study are as follows:

- The uniaxial tensile strength of Ti-Al LMCs decreased with increasing temperature. The ultimate tensile strength showed more pronounced decrease after 100 °C temperature.
- Number of bilayers did not significantly affect the ultimate tensile strength value above the 100 °C test temperature.
- In general, higher yield strength values were obtained in the X samples than in the Y samples.
- As a result of the temperature increase, the YS and ultimate tensile strength values converge to each other.
- The effect of the test temperature on the elongation was observed in at most 5 bilayers.
- When the temperature increased from 100 °C to 200 °C, there was an obvious increase in elongation. The maximum elongation (0.42) was observed in 5 bilayer Y sample at 300 °C. The obtained highest elongation of 5 bilayer Y sample needs further investigation to reveal the detailed explanation.

Acknowledgement

First author acknowledges the support from Anadolu University (Grant #. BAP-1705F248 and #.BAP-1706F382).

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