4-1-2013

Advanced Analysis of Curved and Corrugated Titanium Aluminide Metal Intermetallic Laminates Utilizing Multi-Dimensional Finite Element Analysis

Ryan L. Shrout
Olivet Nazarene University, rshrout@olivet.edu

ADVANCED ANALYSIS OF CURVED AND CORRUGATED TITANIUM ALUMINIDE

METAL INTERMETALLIC LAMINATES UTILIZING MULTI-DIMENSIONAL

FINITE ELEMENT ANALYSIS

By

Ryan L. Shrout

Honors Capstone Project

Submitted to the Faculty of

Olivet Nazarene University

for partial fulfillment of the requirements for

GRADUATION WITH UNIVERSITY HONORS

March, 2012

BACHELOR OF SCIENCE IN ENGINEERING,

in

Engineering (Mechanical Concentration)

Ken Johnson Capstone Project Advisor (printed)	[signature] Signature	3-25-13 Date
CHARLES W. CARRIGAN Honors Council Chair (printed)	[signature] Signature	4/26/13 Date
Janna R. McLean Honors Council Member (printed)	[signature] Signature	4/29/13 Date

This paper is dedicated to the men and women serving in the United States' Armed Forces, and all who will serve in the years to come. May such research as this, to better protect and save lives, never cease.

ACKNOWLEDGEMENTS

I would like to thank the Honors Council for graciously allowing me to work my Honors Scholarship Project into my one year Engineering Senior Design project. I would also like to thank the Engineering Department for allowing me to work on my Honors Scholarship Project as part of my Engineering Senior Design project.

I would also like to thank two donors to the Honors Program Scholarship Fund and the ONU Engineering Department for purchasing a Rockwell Hardness Tester to aid in my research, as well as N.I. Industries and Solidica Inc. for providing me with test samples, specifically John Sheridan and Jay Belle Isle.

Lastly I would like to thank Dr. Ken Johnson, my faculty mentor, for his great advice, large vocabulary and patience, and Sam Crupper and Peter Robinson, my teammates for the Engineering Senior Design project who have been invaluable in encouraging me along the way as well as being accommodating of my needs to work on this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Titanium-aluminide (Al_3Ti) is a high strength per density intermetallic compound that has fascinating implications in the realm of lightweight materials. Such a composite laminate can be thermally reacted from titanium and aluminum foils in an open air heated press. While maintaining many benefits of both materials, its inherent hardness and lack of ductility results in its inability to be conventionally formed into shapes after the reaction occurs. This project developed a method of manufacturing titanium/titanium-aluminide laminate composites in a corrugated geometry. Research and experimentation was conducted to determine the benefits of the curved material. The results suggest a possible change in manufacturing methodology from a sinusoidal corrugation to an angular corrugation.

Keywords: Titanium-aluminide, intermetallic, laminate composite, corrugated

INTRODUCTION

Solidica and NI Industries are currently developing high quality titanium/titanium-aluminide (Ti-Al_3Ti) metal – intermetallic laminate plates, called DuraTi™ for use in military applications. These plates are created by layering Cp-Grade2 titanium (Ti) [1] and AL-1100 aluminum (Al) [2] sheets in a press with specially designed heating elements that apply very high and specific pressure and heat over an extended period of time [fig. 1]. Currently these parts have only been made in flat plates and no successful attempt has been made to create parts with curves in them. My engineering Senior Design team was tasked with finding ways to manufacture curved parts out of Ti-Al_3Ti.

For my Honors research project, while my team (myself included) worked on creating a way to manufacture pieces of DuraTi™ with alternative geometries for the N.I. / Solidica Senior Design Project, I examined the ballistic implications (both positive and negative) of shaped DuraTi™ in relation to standard plate DuraTi™, with specific focus given to the aforementioned metal-intermetallic laminate (MIL), Ti-Al_3Ti.

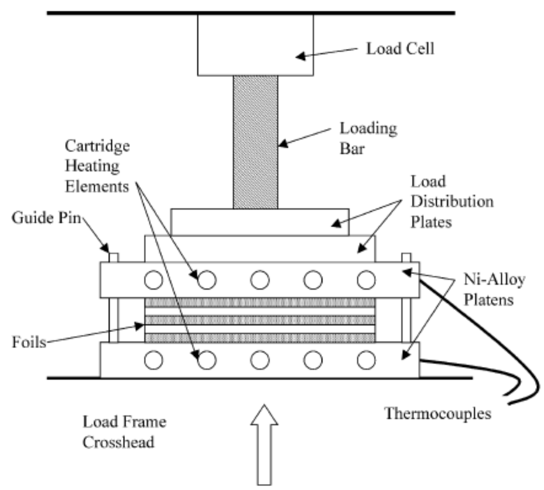


Figure 1- Ti-Al_3Ti MIL Press [3]

This paper considers non-planar MIL geometries and examines their similarities to, and differences from, flat plate Ti-Al_3Ti to see if such geometries would be feasible for use in select rugged applications where weight reduction is desired. Suggestions are made for future non-planar MIL geometries based on the research.

REVIEW OF LITERATURE

Armor plating has many varied applications, from personal protection in the form of bulletproof vest inserts to forming impact resistant shells surrounding large military vehicles such as tanks. Regardless of application however, there is the constant struggle to reduce weight, thus increasing maneuverability, while increasing the level of protection [4], and of course, lowering costs is always important as well [5]. One effective way to address these issues is to use shaped armor. For instance, a curved piece of armor could be used to cut off a sharp corner that would otherwise be made by two flat plates of armor, thus lightening the weight, eliminating a weak welded seam, and lowering the cost.

The current standard in lightweight armament for most applications is ceramic composite armor. Ceramics are equally good at stopping projectiles as ballistic resistant steels, at a fraction of the weight. Their high hardness makes for an ideal strike face for defeating incoming projectiles, especially when paired with a polymer matrix composite backing (such as Kevlar™) to form a composite armor system. The problem is that the high hardness of ceramics results in their highly brittle nature and they are unable to be bent into different geometries once they are formed. They will also shatter upon hard impact, rendering the entire ceramic tile that was struck relatively useless against defeating subsequent shots [6]. For that reason, ceramic armors are usually made up of an array of many small ceramic tiles [fig. 2], but this makes them costly to produce.

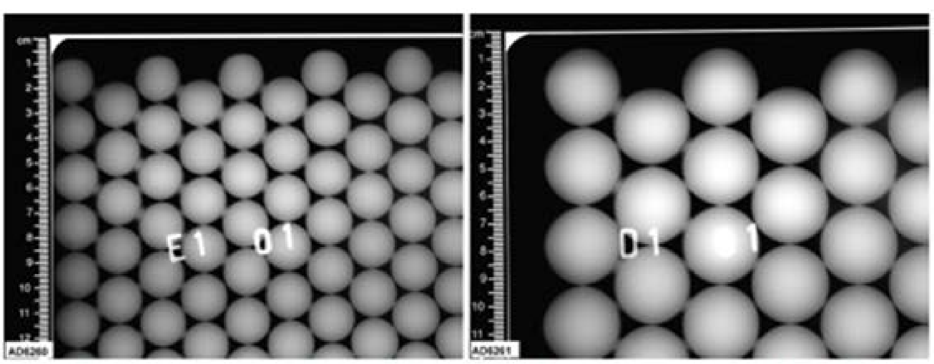


Figure 2- Varying Sizes of Ceramic Tiles in an Array [7]

Ballistic steel, though easier to produce in varying geometries than ceramics and less expensive, is much heavier. The search for a solution to this trade-off between cost and weight has led to the development of metal-intermetallic laminate (MIL) composites [8]. Ti-Al_3Ti is arguably the best option currently in development, in that it is much easier and cheaper to fabricate [9]. Unlike many other metal-intermetallic laminates, the Ti-Al_3Ti composite can be synthesized by reacting easily obtainable and affordable aluminum and titanium foils, sintering them in an open air heated press, instead of necessitating a specific gas filled vacuum chamber as many other such reactions require [3]. Ti-Al_3Ti MIL is manufactured by heating these foils under pressure to exceed the melting temperature of the aluminum (nearly 700 degrees centigrade) which causes the phase changing aluminum to react with the still solid titanium sheets, creating the high hardness intermetallic, Al_3Ti, bonded in alternating layers with the more ductile residual titanium metal [9]. This provides repeating instances of the formula for ceramic composites mentioned previously, with a high hardness strike face and a more ductile metallic backing in lieu of a polymer matrix composite. The intermetallic, Al_3Ti, acts similarly to a ceramic in that it will erode and rupture incoming projectiles, despite having a low fracture toughness [6]. The residual titanium layers provide a more ductile backing to the Al_3Ti, and are much less likely to fracture on impact, but rather plastically deforming and absorb the energy from the incoming projectile, as well as creating a barrier to keep the fractures from propagating from one intermetallic layer to another [10].

Titanium/titanium-aluminide is a nearly ideal material in that it combines the benefits of metals and ceramics, all within a metallic atomic lattice system. It has very high hardness, high modulus of elasticity, low density, high melting temperature and can also be welded with conventional welding methods. Ti-Al_3Ti MIL composites offer a strong combination of Fracture Toughness / Density, and Young's Modulus / Density [11] [fig. 3]. These high specific values make Ti-Al_3Ti a very attractive ballistic resistant material for its combination of light weight and high toughness [13]. It is also much cheaper than ceramics; DuraTi™ Ti-AL_3Ti can be purchased in volume for roughly a quarter of the price of high performance ceramics [8]. However, titanium-aluminide is still disadvantaged in that its relatively brittle, high hardness intermetallic layers cannot be bent and therefore the material cannot be shaped after it has been manufactured.

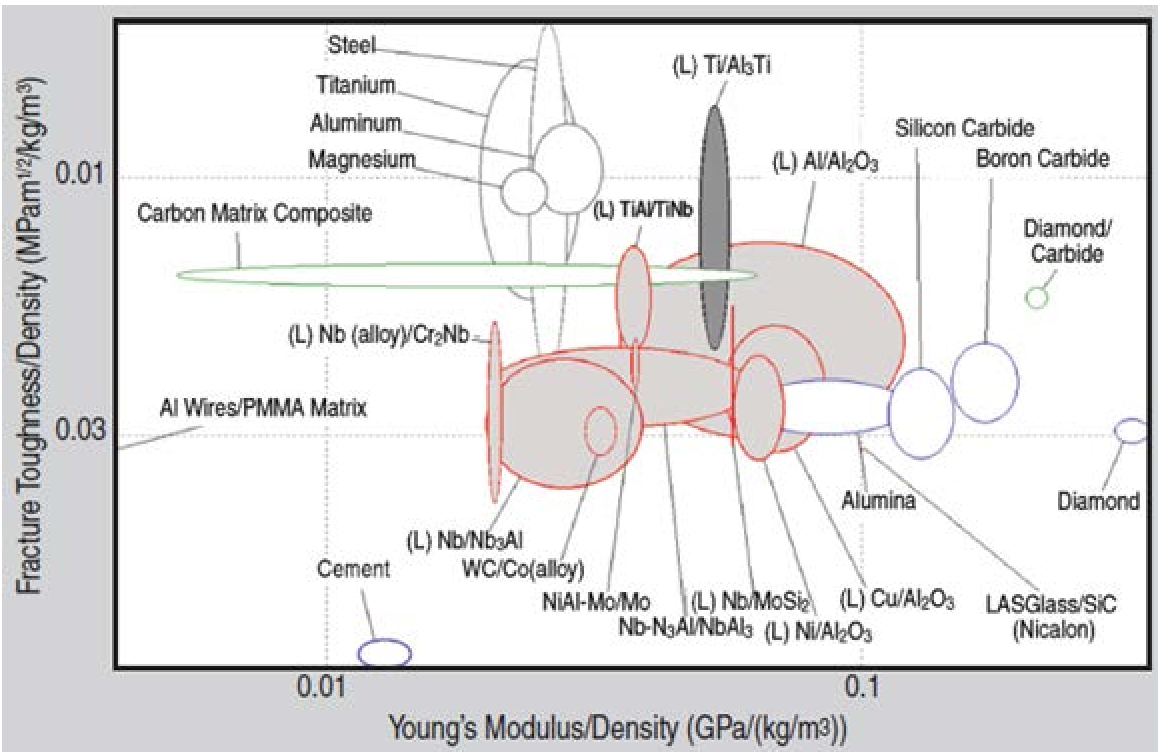


Figure 3- Specific Values per Density [12]

The primary purpose and use of this technology is expected to be in the area of lightweight material, both in large sized pieces for military vehicles such as light armored vehicles (LAVs) and smaller sized pieces for individual body protection. The material would be better suited to both of those uses if it could be manufactured in curved and corrugated parts, however it is well suited for material replacement applications even in its current, flat plate state. This provided the basis for my testing; the goal being to see if alternate geometries would maintain the capabilities of flat plate Ti-Al_3Ti MIL, or maybe even improve them.

Being able to achieve the production of shaped pieces of this material would only further serve to improve upon the above mentioned advantages of Ti-Al_3Ti MIL over existing lightweight materials. Tests have proven that the specific molecular structure found within the laminate composite demonstrates a predictable damage evolution [14], and that glancing blows, such as would be more common for a curved piece, will cause significantly less damage to the laminate as a whole, thus making it more resilient [15].

A projectile, when striking a hard surface at an angle will begin to erode the strike face as well as itself where the two are in contact. This creates asymmetrical forces acting on the projectile and causes it to rotate more parallel to the strike face and in some instances ricochet instead of penetrating deeper into it [16]. In the case of a corrugated configuration, such a turn will lead the projectile into another part of the plating after having already begun the process of eroding and tumbling the threat. Furthermore, even if penetration is achieved, the projectile will have been caused to deviate from its intended trajectory.

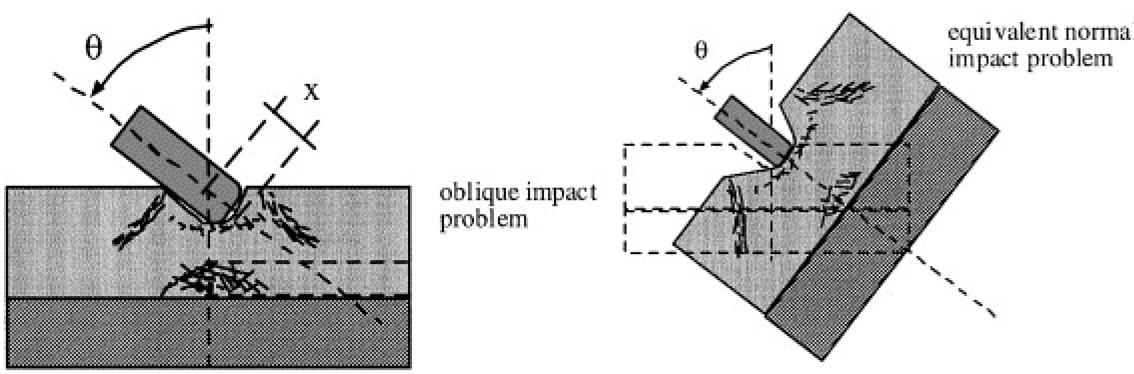


Figure 4- Equivalent Normal Penetration [17]

In addition, angled surfaces are more difficult to penetrate because they cause an increase in the "line-of-fire (LOF) thickness" [fig. 4], thus resulting in a higher ballistic limit. The ballistic limit of a material is defined as the minimum velocity at which a projectile is expected to consistently penetrate a given material, and beneath which velocity the material is expected to consistently defeat the same projectile [18]. When the target is struck at an angle, its effective thickness is equal to its actual thickness divided by the cosine of the angle of obliquity at which it is struck ($t_{LOF} = \frac{t}{\cos(\theta)}$). This results in less material being necessary to defeat an incoming projectile and therefore greater weight saving. A study presented at the 2001 *International Symposium of Ballistics* even reported that because of the previously mentioned tumbling effect, higher obliquities would result in further weight savings than would be calculated from the inverse cosine equation alone [19].

While the ballistic limit will consistently increase as obliquity also increases, the weight savings do not as it takes more material to cover less horizontal target area, resulting in a lower ratio inclined areal density to normal areal density [20]. An armor's areal density is its weight per unit area, therefore the closer the areal density ratio ($^{AD_\theta}/_{AD_n}$) is to one, the less weight penalty would be incurred [18]. The turning point in this trade off seems to be at about thirty-five to forty degrees, as the obliquity benefits begin to increase less rapidly while the weight penalty continues to increase linearly [20].

With that in mind, the problem becomes finding a method of manufacturing Ti-Al_3Ti MIL composite pieces with such a curvature. The decision was made to attempt to make a sinusoidal corrugate sheet using half stainless steel rods, welded to thin plates at the top and bottom of the press [21]. The following experimentation was done to determine the effectiveness of this manufacturing method and suggest appropriate changes for future attempts.

MATERIALS AND METHODS

All titanium titanium-aluminide samples were produced by Solidica, Inc. in partnership with N.I. Industries. Specimens for microscopy and hardness testing were cut, ground, polished, and set in phenolic mounts in Ann Arbor, MI before being shipped to Olivet. These specimens were kept beneath a protective cap unless being tested or analyzed to avoid any unnecessary scarring. Specimens were received from two standard, flat plate DuraTi™ pieces one from each quadrant of each piece. These were enumerated as Sample Set S2: 1, 2, 3, 4 and Sample Set S4: N, S, E, W. In addition, two specimens were received from two different initial attempts by Solidica, Inc. to create corrugated DuraTi™, enumerated as C1 and C2.

All of these specimens were carefully examined under a Leica M125 compound microscope and documented with a Leica DFC425 camera mount attachment via the Leica Application Suite software. This initial analysis allowed for qualitative assessment of the various production methods and comparisons between the flat and curved Ti-Al_3Ti, searching for variations in uniformity within each specimen as well as cracks and failures. After the initial microscopy runs, the specimens were all subjected to hardness testing on a Wilson Instruments, Rockwell 574 Hardness Testing Machine. All tests were run on the Rockwell “B” scale, with a one-sixteenth inch (1.5875 mm) silicon carbide ball indenter, a 10 kgf minor load, a 100 kgf major load, and a dwell time of two seconds. The Rockwell “B” scale is dimensionless and has a maximum value of 130, from which is subtracted the height of the indentation divided by two one-thousandths ($130 - h/.002$) [22].

Each individual specimen was tested multiple times and the values recorded. For each striking of the specimen, the testing indenter was targeted towards the center of a titanium-aluminide layer. For the eight flat plate specimens, the first hardness test was run in the lower left corner, and each successive test moved up a layer and to the right by approximately three millimeters [fig. 5]. Due to the destructive nature of this test, any poor striking that occurred could not be redone and the data point would be thrown out. Data was collected and grouped by specimen and statistical calculations were made to determine the mean, standard deviation, and range.

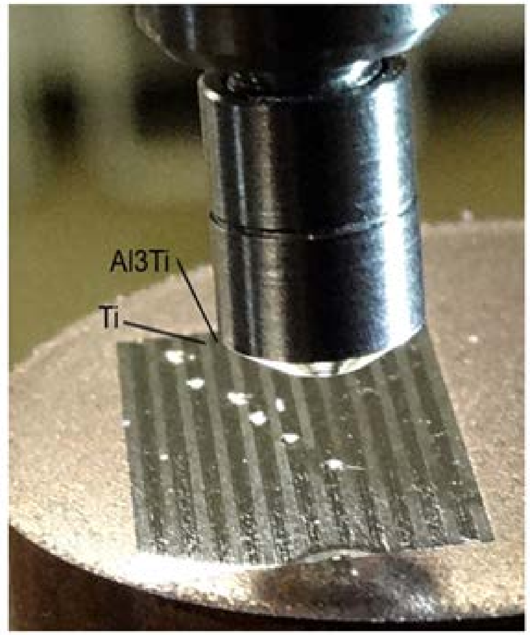


Figure 5 – Hardness Test Specimen

For the two specimens from the corrugated DuraTi™ pieces, the laminate composition was somewhat muddled and the individual layers were much thinner, making it impossible to target a specific layer. Instead, each specimen was struck ten times at a variety of locations and position types relative to the corrugation curves. Once again data was collected and grouped by specimen with statistical calculations done to determine mean, standard deviation, and range. Since the goal of this research was to determine if curved titanium – titanium-aluminide laminates were feasible alternatives to flat plate armor, all of the datum points were considered without discarding outliers.

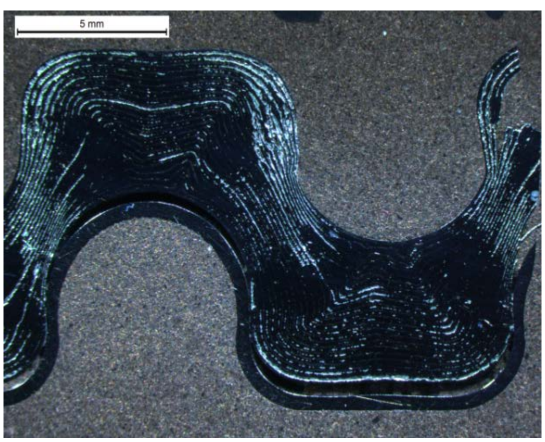


Figure 6 – Corrugated Test Specimen

After hardness testing all of the specimens, more microscopy was done to connect the hardness test values to their locations on each specimen within the laminate layers and to try and explain why certain locations had higher or lower values.

RESULTS

In the tables below are the arithmetic mean, standard deviation, and range from each set of data collected after removing the datum points from the failed tests. There are no units for hardness, as it is an arbitrary numbering system based upon whichever scale is being used. All of this data was obtained on the Rockwell B scale. The data from the flat samples was largely consistent within the sample set and with within the range of expected values.

S2	(2_1)	(2_2)	(2_3)	(2_4)	S4	(4_N)	(4_S)	(4_E)	(4_W)
Mean:	102.57	109.7	110.16	109.7	Mean:	110.16	109.74	108.04	109.65
Std. Dev.:	1.37	0.46	1.37	0.46	Std. Dev.:	1.94	1	1.25	0.88
Range:	0.2	1.2	3.2	1.2	Range:	6	2.8	3.9	2.8

Table 1- S2 and S4 Hardness Statistics

Occasional bad trials in the S2 and S4 sample sets were caused by striking a titanium layer, either partially or fully, with the indenter instead of the titanium-aluminide layer. This resulted in a drop in the hardness reading from five percent to thirty percent beneath what would otherwise be expected, which is consistent with the known hardness value of titanium and the observed location of the indenter strike. The other rare cause of a bad data point was pre-existing damage to the specific titanium-aluminide layer being tested. Also of note, the base of the phenolic casing of specimen S2_1 was slightly uneven which led to marginally lower values. The complete collection of data received from the hardness testing can be found in Appendix 1.

The two corrugated specimens each came from separate prototype plates. The C1 specimen was cut from a plate with a wider radius of curvature and the C2 specimen was cut from a plate with a tighter radius of curvature.

	C1	C2
Mean:	100.77	82.77
Std. Dev.:	5.33	13.76
Min:	89.1	57.3
Max:	106.8	98.8
Range:	17.7	41.5

Table 2- C1 and C2 Hardness Statistics

Neither sample was consistent across the specimen and the hardness values varied greatly depending on where on the specimen they were taken and how the laminate layers had formed. None of the data points were thrown out for these two specimens, resulting in a large range and standard deviation. The highest values for both occurred in the straight edges and the inside corners of the curves.

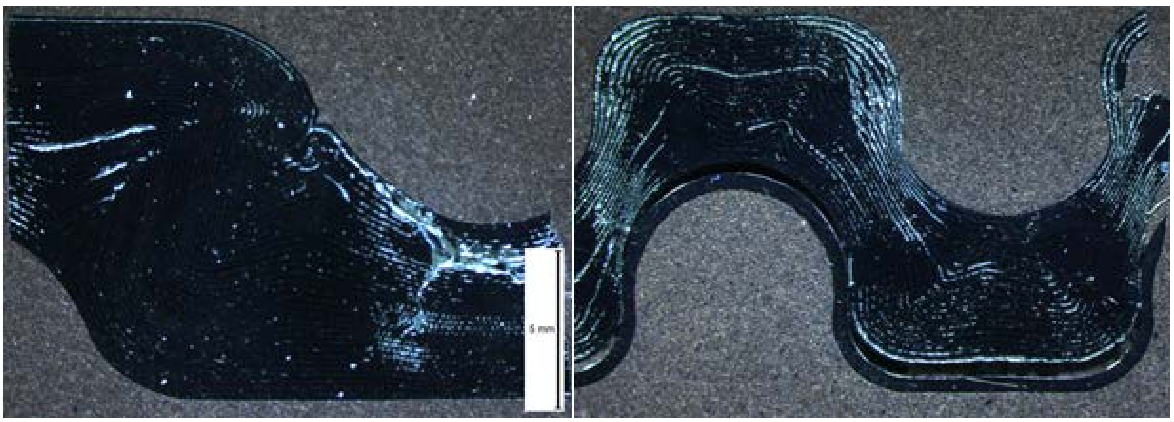


Figure 7 – C1 and C2 Corrugated Samples

The initial microscopy showed both corrugated specimens to have significantly thinner laminate layers than the flat plate specimens, making it so that all strikes by the hardness tester were guaranteed to at least partially hit on a Ti layer. With this in mind, the overall results from piece C1 were consistent with results from the partial and complete Ti hits that were thrown out of the S2 and S4 data sets. C1 was also a more consistent piece in general, with a smaller range of hardness values and tighter laminate layers forming into a linear pattern rather than a curved pattern. Specimen C2 with its tighter radius of curvature featured a more defined inflection point than C1 with curvier transitions. Both the curves and inflection points in sample C2 were locations of weakness. It is worth noting that the mean hardness value for C1 is higher than the maximum hardness value found in C2, and that the mean hardness value of C2 is lower than the minimum hardness value found in C1. Once again, all of the collected data can be found in Appendix 1 and more microscopy images can be found in Appendix 2.

DISCUSSION

With the exception of the specimen S2_1, which had the uneven base as mentioned in the Results section, all of the flat plate specimens provided a very consistent base line with average hardness values of the titanium-aluminide layers ranging from 108 to 110 on the Rockwell B scale. This value on other scales converts to 68 Rockwell A, 336 Brinell 3000kg, 354 Vickers, and 49 Shore [23]. These numbers are comparable to known hardness test values of pure titanium-aluminide. Furthermore, the phenolic casing that the specimens were mounted in was soft relative to the specimens themselves, and though it offered a large surface area for the pressure of the indenter to spread out over, it was sure to have some effect on the calculated hardness value. Thus the actual hardness value for all of the data points is likely higher than reported.

The testing done on the corrugated armor yielded some interesting information, some of it expected and some of it not. Expected was that the highest hardness values in the corrugated specimens were not as high as the mean hardness values of the flat plate specimen. This is most likely because the laminate layers found in the corrugated specimens were much thinner and partially hitting a Ti layer with the hardness indenter was unavoidable. Prior research has shown that in composite armors, thicker high hardness layers result in a higher ballistic limit [24]. Unexpected was the fact that within the corrugation curves, the laminate structure crinkled to try and form itself into as straight a line as possible, creating corners instead of curves. Furthermore, hardness test data from those areas showed that the tight radius on the inside of those corners yielded higher hardness values than the larger radius on the outer edge which formed more of a curve than a corner. Still, data drawn from the straight, flat sections produced the best results in both specimens.

It was also shown that the inflection points in the approximately sinusoidal pattern tended to cause the most problems and deliver the lowest hardness values. It seemed that in the formation process, the layers all delaminated. Though it would be difficult to strike that area of the corrugation curve with a projectile, its weakness would still adversely affect the rest of the armor. However, the fact that the laminate structure was better able to properly form further from the inflection point, while still in a vertical configuration relative to the press during manufacturing confirms that the current method of sintering foils in an open air press is still valid for non-planar geometries.

*****This section redacted due to sponsor proprietary rights*****

Further testing on this subject could be done by repeating the current methodology with new and different geometries. In addition to microscopy and hardness testing, live fire ballistic testing, according to certified codes and standards [26], would also be useful to ascertain how a full scale part would do against real ammunition, though such tests are costly to conduct.

CONCLUSION

This project set out to determine if new methods for producing curved and corrugated pieces of Ti-Al_3Ti metal – intermetallic laminate composite armor were feasible alternatives to the existing flat plate MIL composite armors, and to test them to ascertain what benefits might come from such geometries. Samples from prototype corrugated MIL composite plates as well as previously made flat plate DuraTi™ material were carefully studied under a microscope, submitted to hardness testing, and reexamined under the microscope. The results suggested that future attempts to manufacture corrugated Ti-Al_3Ti MIL composites should take on an alternative shape to achieve greater reaction regions, higher consistency, and higher net material hardness values. Research should continue on this topic, as it has the potential to directly impact the safety and protection of military personal and police forces.

REFERENCES

[1] Supra Alloys Inc., "*Material Certification,*" December 2011.

[2] Skana Alluminum Company, "*Certification of Properties,*" March 2012.

[3] K. S. Vecchio and D. Harach, "Microstructure evolution in metal-intermetallic laminate (MIL) composites synthesized by reactive foil sintering in air," *Metallurgical and Materials Transactions,* vol. 32A, pp. 1493-1505, June 2001.

[4] T. Kelly, et al, "Observations and Conclusions," in *The U.S. Combat and Tactical Wheeled Vehicle Fleets: Issues and Suggestions for Congress*, Santa Monica, CA, RAND Corporation, 2011, ch. 6, sec. 3, p. 108.

[5] "GlobalSecurity.org," [Online]. Available: http://www.globalsecurity.org/military/library/report/2011/2011-army-twv-strategy.htm. [Accessed 25 October 2012].

[6] M.M. Shokrieh and G. H. Javadpour, "Penetration analysis of a projectile in ceramic composite armor," *Composite Structures,* vol. 82, no. 2, pp. 269-76, January 2008.

[7] R. Klement, et al, "Transparent armor material," *Journal of European Ceramic Society*, vol. 28, no. 5, pp. 1091-95, 2008.

[8] J. Sheridan, *Lightweight Materials Briefing,* 2012.

[9] L. M. Peng, et al, "Synthesis and microstructural characterization of Ti-Al3Ti metal-intermatallic laminate (MIL) composites," *Scripta Materialia,* vol. 52, no. 3, pp. 243-48, February 2005.

[10] D. Price, et al, "Effects of ductile phase volume fraction on the mechanical properties of Ti-Al3Ti metal-intermetallic laminate (MIL) composites," *Materials Science and Engineering,* vol. 528, pp. 3134-46, January 2011.

[11] K. Vecchio, "Process for making metallic/intermetallic composite laminate materian and materials so produced especially for use in lightweight armor". United States of America Patent 6,357,332 B1, 19 March 2002.

[12] K. S. Vecchio, "Synthetic multifunctional metallic intermetallic laminate composites," *Journal of the Minerals, Metals, and Materials Society,* vol. 57, no. 3, pp. 25-31, March 2005.

[13] B. E. Hurless and F. H. Froes, “Lowering the cost of titanium,” *Amptiac Quarterly*, vol. 6, no. 2, pp. 3-9, December 2011.

[14] T. Li, et al, "Modeling the elastic properties and damage evolution in Ti-Al3Ti metal-intermetallic laminate (MIL) composites," *Materials Science and Engineering,* vol. 374, no. 1-2, pp. 10-26, June 2004.

[15] Z. Fawaz, et al, “Numerical simulation of normal and oblique impact on ceramic composite armors,” *Composite Structures*, vol. 63, pp. 387-95, 2004.

[16] A. Tate, “A simple estimate of the minimum target obliquity required for the ricochet of a high speed long rod projectile,” *Journal of Physics and Applied Physics*, vol. 12, pp. 1825-29, 1979.

[17] R. Zaera and V. Sanchez – Galvez, “Analytical modeling of normal and oblique ballistic impact on ceramic / metal lightweight armours,” unpublished.

[18] Department of Defense, "*Test Method Standard -* V_{50} *Ballistic Test for Armor*," 18 December 1997.

[19] D. Yaziv, et al, "Oblique penetration in ceramic targets," in *19th Int. Symp. of Ballistics*, Interlachen, Switzerland, 2001, pp. 1257-64.

[20] S. Sadanandan and J. G. Hetherington, "Characterization of ceramic/steel and ceramic/aluminum armors subject to oblique impact," *International Journal of Impact Engineering*, vol. 19, no. 9-10, pp. 811-19, October – November 1997.

[21] J. Sheridan, "*Corrugated DuraTi R&D Notes*," personal communication, December 2012.

[22] *Rockwell 574 Hardness Testing Machine*, Wilson Instruments, Norwood, MA, 2009.

[23] "Carbide Depot," [Online]. Available: http://www.carbidedepot.com/formulas-hardness.htm [Accessed 20 March 2013].

[24] P.Gallagher, "*Armor Introduction*," Dynalytics, Inc. Briefing, 2010

[25] J. Sheridan, "Angular *Corrugated DuraTi*," personal communication, January 2013.

[26] "Craig International Ballistics," [Online]. Available: http://www.ballistics.com.au/technical/ballisticandstabstandards.php#stanag. [Accessed 28 October 2012].

APPENDIX 1

Hardness Test Data

Sample Set 2

Red Values Thrown Out

2_1 *Base of specimen was uneven.*

strike	Hardness			
1	85.6	*Layer had pre-existing crack.*		
2	85.6	*Layer had pre-existing crack.*		
3	102.7		Mean:	102.57
4	102.5		Std. Dev.:	1.37
5	102.5		Range:	0.2

2_2

strike	Hardness			
1	80.3	*Partially on Ti layer.*		
2	109.5			
3	109.5		Mean:	109.7
4	110.5		Std. Dev.:	0.46
5	109.3		Range:	1.2

2_3

strike	Hardness			
1	80.1	*Layer had pre-existing crack.*		
2	110.7			
3	112.3		Mean:	110.16
4	111.5		Std. Dev.:	1.37
5	109.1		Range:	3.2

2_4

strike	Hardness			
1	X	*Layer had pre-existing crack.*		
2	108.2		Mean:	109.7
3	110.2		Std. Dev.:	0.46
4	108.6		Range:	1.2
5	86.1	*Too close to specimen edge.*		

Sample Set 4

Red Values Thrown Out

4_N

strike	Hardness	
1	78.3	*Struck on a Ti layer*
2	106.5	
3	112.5	
4	111.7	
5	109.5	
6	110.5	
7	110.1	
8	110.3	
9	102.4	*Partially on Ti layer*

Mean:	110.16
Std. Dev.:	1.94
Range:	6

4_E *Slightly thinner Al3Ti layers*

strike	Hardness	
1	78.7	*Struck on a Ti layer*
2	106.1	*Partially on Ti layer*
3	108.4	
4	106.1	*Partially on Ti layer*
5	107.6	
6	110	
7	108.1	
8	104.5	*Partially on Ti layer*
9	103.2	*Partially on Ti layer*

Mean:	108.04
Std. Dev.:	1.25
Range:	3.9

4_S

strike	Hardness	
1	76.1	*Struck on a Ti layer*
2	110.6	
3	107.8	
4	110.4	
5	109.9	
6	110	
7	105.6	
8	105.8	
9	X	*Specimen had one less layer*

Mean:	109.74
Std. Dev.:	1
Range:	2.8

4_W

strike	Hardness	
1	89	*Struck on a Ti layer*
2	109.2	
3	111.1	
4	109.6	
5	109.5	
6	110.7	
7	109.2	
8	108.3	
9	101.3	*Partially on Ti layer*

Mean:	109.65
Std. Dev.:	0.88
Range:	2.8

Corrugated C1 and C2

Best 3	Worst 3

All Values Considered

C1

strike	Hardness
1	89.1
2	106.8
3	103.7
4	98.3
5	100
6	99.4
7	95.2
8	102.7
9	106
10	106.5

Mean:	100.77
Std. Dev.:	5.33
Min:	89.1
Max:	106.8
Range:	17.7

C2

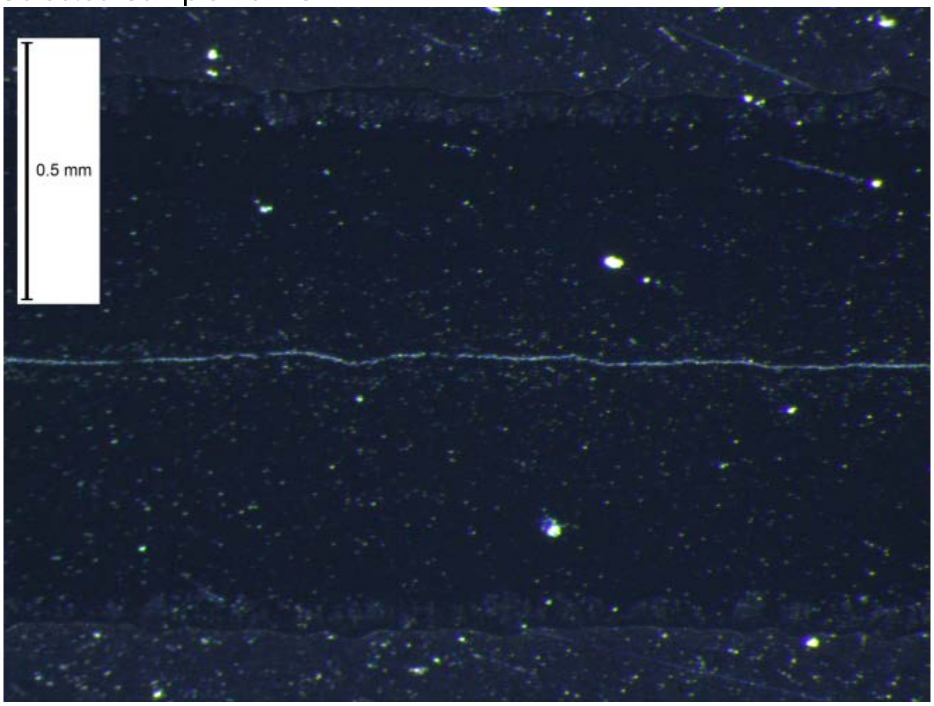
strike	Hardness
1	72.8
2	61.2
3	57.3
4	91.9
5	98.2
6	86.7
7	85.1
8	91.7
9	98.8
10	84

Mean:	82.77
Std. Dev.:	13.76
Min:	57.3
Max:	98.8
Range:	41.5

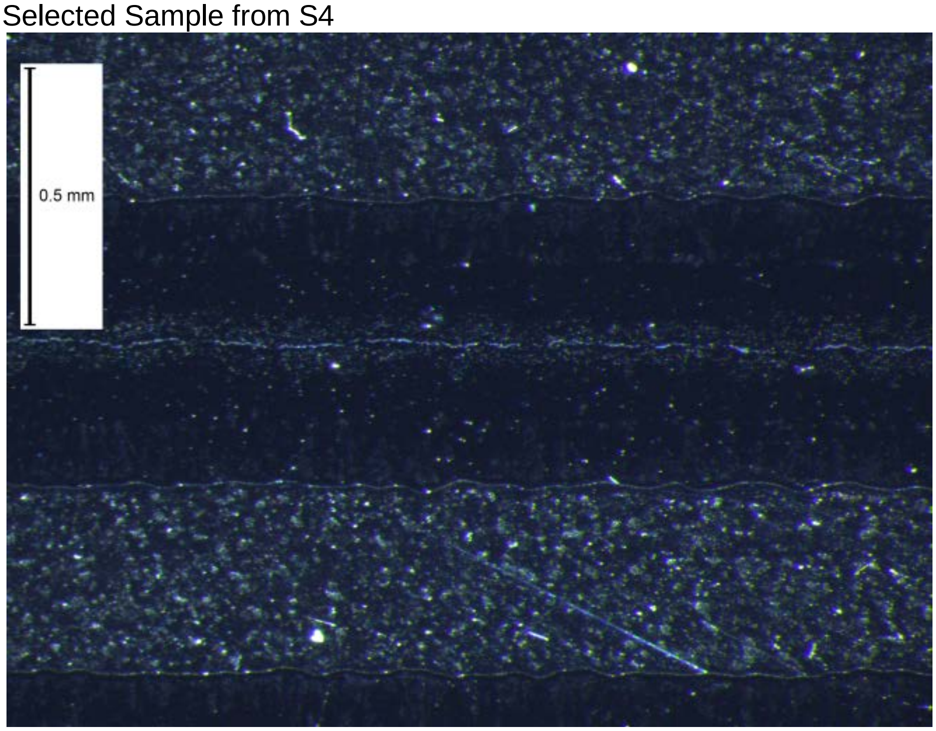
APPENDIX 2

Select Microscopy Images

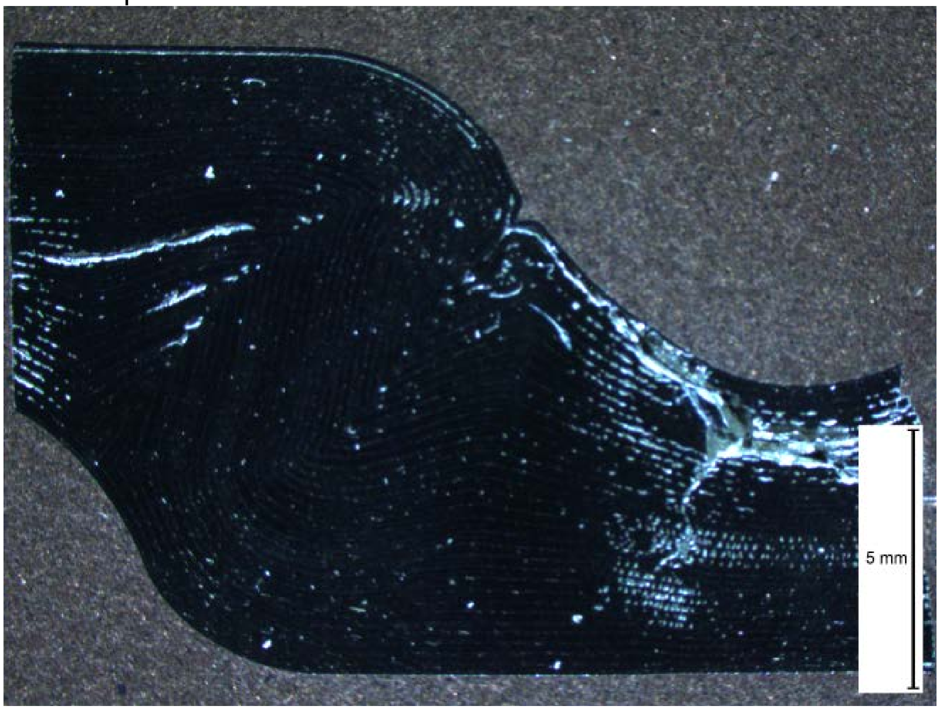
Selected Sample from S2



Selected Sample from S4



Full C1 Specimen



Full C2 Specimen