ACKNOWLEDGEMENT

I wish to express my sincere gratitude and great appreciation to my supervisor *Assistant Prof. Adel K. Mahmoud* for his supervision, encouragement and valuable comments which have been very helpful to me.

My sincere gratitude and great appreciation to the team of the experimental part of the present work: Professor of material creation, *Prof. Sadrnezhaad*, co-supervisor, Sharif University of Technology (SUT)- Iran, Visiting Professor (MIT)-USA; Professor of welding, *Prof. Kokabi*, SUT; *Dr. M.J.Torkamany*, Specialist of laser welding, Iranian National Center for Laser Science & Technology (INLC) and Mr. *Nasoodi*, microstructure observation laboratory, SUT.

My sincere gratitude and great appreciation to *Prof. Abdul Hadi* **Al-Janabi**, Dean of Institute of Laser for Postgraduate Studies, University of Baghdad, for supporting and facilitating the paper work of my six months research visit.

My sincere gratitude and great appreciation to **Prof. Hussein Ali** Jawad, as well as to all the staff of the institute for support and guidance during the research period.

I would like to express my sincere gratitude to the Iraqi *Ministry* of *Higher Education and Scientific Research* for offering the six months research mission in Sharif University of Technology SUT- Iran

Finally no wards can be said to my family for their love, patience, understanding and unconditional supporting accomplishing this tough journey of learning.

Abeer

ABSTRACT

Materials titanium and aluminum are of technological interest in automotive, aerospace and smart sensor industries. The challenges for welding them result from the large difference in thermophysical and mechanical properties, besides limited solubility of each metal in other. Thus welding them using laser, will reduce intermetallic phases (IMP) formation to acceptable limits, since the weld itself is narrow.

In the present work a special form of laser spot welding is introduced to joint overlapped titanium Ti Grade 2 to 3105-O aluminum alloy, with 1 and 0.5 mm thicknesses respectively. A welding tactile seam tracking design using following pulses that result to a circular seam, leads to spot like shape laser welding. For this study, laser welding parameters were: pulse energy 11 J; pulse duration 6ms; pulse frequency 20Hz; argon gas flow rate 20 l/m and welding speed (4 - 6.7) mm/s.

Welding speed was observed to have the strongest effect on heat input, where 4 mm/s (76% overlapping) speed has led to better energy absorption and wider more uniform melted area at Ti-Al interface, thus 70 MPa joint strength was obtained. Examination of the joint region using scanning electron microscopy (SEM), energy dispersive X-ray spectrometry (EDS) and X-ray diffraction (XRD) showed the formation of different IMP in the Ti-Al welding zone. Ti fusion zone (FZ) near the interface was mainly containing Ti₃Al. Crakes were observed in Al (FZ) near the interface as a result of mechanical and thermo physical properties gradient.

Inorder to reduce IMP formation and relaxes the high gradient in thermophysical and mechanical properties in the welding zone, four fillers metals (Al-5Si, Al-12Si-2.5Mg, pure Nb and Al-0.2Sc-0.36Zr), with three different thicknesses for each filler, were prepared. Al-5Si filler has positive effect on the joint strength where Si has reduced the IMP harmful effect via replacing Al atoms substitutionaly in TiAl₃ at the interface, thus joint strength was increased to 80MPa instead of 70MPa. Al-12Si-2.5Mg filler has improved the joint strength to 87MPa where the shear strength of Al base metal of 82MPa was exceeded. Due to its high melting point pure Nb filler prevented penetration of bottom Al sheet, thus it was unsuitable to use for the present work conditions. A new Al-0.2Sc-0.36Zr filler was used for the first time in the present work and has very positive impact to the joint strength 103MPa, where the joint has fractured from Al base metal.

In comparison to the corrosion rate of Ti base metal, joints without using filler and with the new Al-0.2Sc-0.36Zr filler metal, have decreased the corrosion rate by 51% and 72% respectively, while joints with Al-5Si and Al-12Si-2.5Mg filler metals, have increased the corrosion rate by 68% and 80% respectively.

الخلاصة

التيتانيوم والالمنيوم مواد تلقى اهتمام تقني في الصناعات الالية والفضائية والمتحسس الذكي التحديات التي تواجه لحامهم هي نتيجة للاختلاف الكبير في المواصفات الثرموفيزيائية والميكانيكية، اضافة الى الذوبانية المحدودة لكل معدن في الاخر ،لذلك لحامهم باستعمال الليزرسيقلل تكوين الا طوار المعدنية الضارة لما كانت منطقة اللحام نفسها ضيقة .

في هذا العمل قدم شكل خاص من اللحام الليزري النقطي لربط تيتانيوم رتبة ٢ تراكبيا مع سبيكة المنيوم O-3105 باسماك ٥.٠, ١ ملم على التوالي، من خلال لحام درز دائري، لبق التصميم يستعمل نبضات ليزر متعاقبة ادت الى لحام شبيه للحام الليزري النقطي لهذه الدراسة كانت معاملات لحام الليزر كالاتي: طاقة النبضة ١١جول، مدة النبضة ٦ ملي ثانية، تردد النبض ٢٠هرتز، تدفق غاز الاركون ٢٠ لتر/دقيقة وسرعة اللحام (٤-٦, ٦٧) ملم/ثانية.

لقد لوحظ ان تأثير سرعة اللحام كان الاقوى على الحرارة الداخلة لمنطقة اللحام حيث سرعة لحام ٤ ملم /ثا (٧٦%عامل تداخل النبضات)، قد ادت الى افضل امتصاص لطاقة الليزر واكثر تجانس و عرض للمساحة المنصهرة عند منطقة تداخل Ti-AI, لذلك تم الحصول على ٩٤٠٧ مقاومة وصلة اللحام. اظهر فحص منطقة وصلة اللحام باستخدام المجهر الماسح الالكتروني SEM، مقياس تشتت طاقة الاشعة السينية EDS ومقياس انحراف الاشعة السينية XRD, تكون الاطوار المعدنية الضارة. المنطقة المنصهرة للتيتانيوم قرب منطقة تداخل Ti-Al ضمت طور Ti₃Al. الشقوق لوحظت في منطقة الالمنيوم المنصهرة قرب منطقة التداخلTi-Al, نتيجة الانحدار العالي في الخواص الميكانيكية والثرموفيزيائية.

من اجل التقليل من تكون الاطوار المعدنية الضارة وتخفيف الانحدار العالي في الخواص . الثر موفيزيائية والميكانيكية، اربعة انواع مختلفة من الحشوات المعدنية

(Al-5Si, Al-12Si-2.5Mg, pure Nb and Al-0.2Sc-0.36Zr)

مع ثلاثة اسماك مختلفة لكل حشوة قد حضرت في هذا العمل. حشوة AI-5Si كان لها تاثير ايجابي على مقاومة وصلة اللحام حيث ان Si قلل التاثير الضار للاطوار المعدنية الضارة من خلال تعويض ذرات AI في Ti₃Al لذلك فان مقاومة الوصلةزادت الىMPa80 بدل MPa70.حشوة AI-12Si ذرات AI في MPa70 لذلك فان مقاومة الوصلة زادت الىMPa80 بدل MPa70.حشوة AI-2Shg ذرات AI في 2.5Mg العملي في MPa82 قد حسنت مقاومة الوصلة الىMPa87 متجاوزة بذلك مقاومة القص AD25 قد حسنت مقاومة الوصلة الىMPa87 متجاوزة بذلك مقاومة القص 2.5Mg الترابط المعدن الاساس AI. نتيجة درجة اانصهاره العالية، حشوة النيبيوم النقي No منعت لحام صفيحة AI المعدن الاساس AI. نتيجة درجة اانصهاره العالية، حشوة النيبيوم النقي No منعت لحام صفيحة AI المعدن الاساس AD3 نتيجة درجة اانصهاره العالية، حشوة النيبيوم النقي ND30 منعت لحام صفيحة AI المعدن الاساس AD3 نتيجة درجة اانصهاره العالية، حشوة النيبيوم النقي ND30 منعت لحام مفيحة AI المعدن الاساس AD3 نتيجة درجة اانصهاره العالية، حشوة النيبيوم النقي ND30 منعت لحام مفيحة AI المعدن الاساس AD3 نتيجة درجة اانصهاره العالية، حشوة النيبيوم النقي معام منعت لحام من المعدن السفلي، لذلك هذه الحشوة كانت غير مناسبة للا ستعمال وفق شروط اللحام لهذا العمل. لقد كان الصفوة الجديدة AI-0.2Sc-0.36Zr التي استعملت لاول مرة من خلال هذا العمل تاثير ايجابي جدا على قوة ترابط وصلة اللحام AD300 حيث ان الكسر حدث من المعدن الاساس AD4 وليس من الوصلة خلال عملية الاختبار. بالمقارنة مع مقاومة التاكل لمعدن التيتانيوم الاساس، اظهرت على قوة ترابط وصلة اللحام 2.5Mg حيث ان الكسر حدث من المعدن التيانيوم الاساس، اظهرت الوصلات بدون استعمال حشوة وباستعمال حشوة AI-0.2Sc-0.36Zr نقصان بمعدل التاكل ب

CONTENTS

AKNOLEDGMENT	i
ABSTRACT	ii
CONTENTS	iv
LIST OF FIGURS	vii
LIST OF TABLES	XV
ABBREVIATIONS	xvii
LIS OF SYMBOLS	xviii
Chapter One: Introduction and Basic Concepts	1
1.1 Introduction	1
1. 2 Joining Process	2
1. 2.1 Mechanical Joining	3

1. 2.2 Adhesive Joining (Chemical Joining)	4
1. 2.3 Welding (Physical Joining)	4
1.3 Laser Metal Interaction	5
1.4 Laser Welding Characteristic Over Other Techniques	11
1.5 Laser Welding Mechanism (Fluid Flow)	13
1.5.1Conduction Welding	15
1.5.2 Keyhole Welding	16
1.6 Pulsed Nd:YAG Laser Welding	19
1.6.1 Pulsed Laser Welding Parameters	22
1.6.1.1 Laser Beam Parameters	23
1.6.1. 2 Processes Parameters	28
1.6.1. 3 Materials Parameters	31
1.6.2 Other Important Parameters	33
1.6.2.1 Joint Design	33
1.6.2. 2 Filler Material	35
1. 6.2.3 Heat Treatment	37
1.7 Metallurgical Aspects of Laser Welding	38
1.7.1Weld Discontinuities	41
1.7.1. 1Hot Cracking	41
1.7.1. 2 Cold Cracking	45
1.7.1. 3 Porosity	45
1.7.1. 4 Macro and Micro Segregation	49
1.8 Weldability	51
1.9 Laser Welding of Aluminum Alloys	52
1.10 Laser Welding of Titanium Alloys	56
1.11 Welding of Dissimilar Metals: Titanium to Aluminum	58
1.11.1 Problems Description for Welding Titanium to Aluminum	59
1.11.2 Corrosion	61
1.11.3 Suggested Solutions for Welding Titanium to Aluminum	65
1.12 Literature Review	68
1.13 The Objectives of the Present Work	75
Chapter Two: Materials and Methods	76
2.1 Introduction	76
2.2 Materials Used and Experimental Procedure	76
2.2.1 Materials Specifications	76
2.2.2 Use and Description of the Used Materials	79
2.3 Specimen Preparation and Joint Design	80
2.31 Specimen Preparation of the Base Metals	80

2.3.2 Specimen Preparation of the Fillers Metals	81
2.3.3 Joint Design and Welding path	85
2.4. Laser Welding	86
2.4.1Apparatus and Equipment	86
2.4. 2 Choice of Laser Welding Parameters and Welding Operations	87
2.5 Post Weld Heat Treatment (PWHT)	89
2.6 Weld Appearance and Microstructure	90
2.7 Mechanical Testing	92
2.7.1 Tensile Strength Testing	92
2.7.2 Tensile Shear Strength Testing	93
2.7.3 Microhardness Testing	93
2.8 Corrosion Testing	93
2.8.1Sample Preparation	94
2.8.2 Corrosion Testing	94
Chapter Three: Results and Discussion	96
3.1 Introduction	96
3.2Welding of ASTM Grade2 Titanium to 3105-O Aluminum Alloy	
Addition of Filler Metal	96
3.2.1 Weld Appearance	97
3.2.2 Weld Microstructures	102
3.2.3 Mechanical Properties	112
3.2.3.1 Shear Strength of the Joint	112
3.2.3.2 Microhardness of the Joint	115
3.2.4 Post Weld Heat Treatment (PWHT)	117
3.3 Welding of ASTM Grade 2 Titanium to 3105-O Aluminum Alloy	' Using
AlSi5(4043) Filler Metal	119
3.3.1 Weld Appearance	119
3.3.2 Weld Microstructures	121
3.3.3 Mechanical Properties	124
3.3.3.1 Shear Strength of the Joint	124
3.3.3.2 Microhardness of the Joint	127
3.4. Welding of ASTM Grade 2 Titanium to 3105-O Aluminum Alloy	Using
AI-12SI-2.5Mg Filler Metal 3.4.1 Weld Appearance	130
3.4.2 Weld Microstructures	130
3.4.3 Mechanical Properties	132
3.4.3.1 Shear Strength of the Joint	137
3 4 3 2 Microhardness of the Joint	141
	1 - 1

3.5 Welding of ASTM Grade 2 Titanium to 3105-O Aluminum Alloy	Using
Al- 0.2Sc-0.36 Zr Filler Metal	143
3.5.1 Weld Appearance	143
3.5.2 Weld Microstructures	143
3.5.3 Mechanical Properties	149
3.5.3.1 Shear Strength of the Joint	149
3.5.3.2 Microhardness of the Joint	152
3.6 Welding of ASTM Grade 2 Titanium to 3105-O Aluminum Alloy	Using
Pure Niobium(Nb) Filler Metal	154
3.6.1 Weld Appearance	154
3.6.2 Weld Microstructures	155
3.6.3 Mechanical Properties	158
3.6.3.1 Shear Strength of the Joint	158
3.6.3.2 Microhardness of the Joint	160
3.7 Corrosion of the Ti-Al Weld Joint	161
3.80verall Results for Joint's Strength and Corrosion Rate	164
3.9 Conclusions and Scope for Future Work	166
3.9.1 Conclusions	166
3.9.2 Thesis Contribution	167
3.9.3 Scope for Future Work	168
References	-

LIST OF FIGURS

Figure 1.1 Classification of joining processes according to American Welding	2
Society AWS	
Figure 1.2 Typical joining types:(a)Mechanical joining, (b) Adhesive joining,	3
(c) Welding.	
Figure 1.3 Power densities vs. interaction times for various laser processes.	11
Figure 1.4 Driving force for the fluid flow in the weld pool: (a) buoyancy	15
force, (b) shear stress of surface tension, (c) shear stress by plasma.	
Figure 1.5 Conduction welding mode.	16
Figure 1.6 Keyhole formation: (a) surface irradiation, (b) surface melting, (c)	17
vaporization and cavity formation, (d) light absorption inside the keyhole.	

Figure 1.7 Illustration of the keyhole shape (a), beam absorption (b).	19
Figure 1.8 Schematic representations of CO2 and YAG laser welding systems	
Figure 1.9 Laser welding parameters	20
Figure 1.10 Output of pulsed laser mode	23
Figure 1.11 Reflectance vs. wavelength for different metals	25
Figure 1.12 Focused laser beam characteristics	25
Figure 1.13 Appearance of laser beam for three different TEM modes,	26
horizontal axis shows increasing distance from the center of the heat source to	
the surface	
Figure 1.14 Absorption vs. welding speed for P and S polarizations	27
Figure 1.15 Different pulse shapes;	27
a. ideal rectangle, b. realistic rectangle, c. ramped up, d. ramped down	
Figure 1.16 Schematic diagram for partially overlapped pulse series	29
Figure 1.17 Penetration versus speed for helium and argon shielding gases	30
Figure 1.18 Reflectivity vs. temperature for different metals	31
Figure 1.19 Laser-welded joints geometries	34
Figure 1.20 Major microstructural zones associated with laser welding	39
Figure 1.21 Effect of cooling rate on grain structure during solidification	41
(a)planar, (b)cellular, (c)columnar dendritic, (d)equiaxed	
Figure 1.22 Mechanical behavior of metals during solidification: (a) narrow	43
brittle range behavior, (b) wide brittle range behavior.	
Figure 1.23 Hot cracking: (a) solidification cracks in fusion zone, (b) liquation	44
cracks in HAZ	
Figure 1.24 Cold cracks in the HAZ of a fillet weld	45
Figure 1.25 Porosity formation during pulsed laser welding of Al:	47
(a) near middle, (b) near end of keyhole	
Figure 1.26 Formation of various types of porosity in laser weld fusion zones	48
of aluminum	
Figure 1.27 SEM photo of the laser weld fusion zone in an aluminum alloy	49

with mapping distribution of Fe, Mg and Si elements	
Figure 1.28 Equilibrium phase diagram of the binary Ti– Al alloy	61
Figure 1.29 Electrode kinetic behavior of a metal (M) in Reducing acid	63
Figure 1.30 Applied current linear-polarization curve (a), experimentally	64
measured polarization resistance (b)	
Figure1.31Variation of crack sensitivity with composition: (a) Al-Si alloy, (b)	66
Al-Mg-Si alloy	
Figure1.32 Strengthening effect of elements on Aluminum	66
Figure 1.33 Recrystallization temperature of cold-rolled binary: Al-Sc , Al-Mn	67
, Al-Cr alloys sheets	
Figure1.34 Phase diagram for Al–Sc binary alloy	67
Figure 2.1 Summery of the experimental producers for the present work.	77
Figure 2.2 Chemical composition analyzer instruments.	78
Figure 2.3The prepared TiG2 and Al 3105 samples.	80
Figure 2.4 Al-5Si filler metal: (a) rods, (b) rolled sheets	82
Figure 2.5 Preparation of Al-12Si-2.5Mg filler metal: casting mold (a), casted	83
Al-12Si-2.5Mg filler metal (b), 1mm thickness wire cut Al-12Si-2.5Mg filler	
metal (c).	
Figure 2.6 AlScZr filler metal sheet production	84
Figure 2.7 Joint design and welding path.	85
Figure 2.8 The designed clamping device.	86
Figure 2.9 Laser welding system (a), welding setup (b).	88
Figure 2.10 Wire cut of the welded samples (a), Buehler mounting press (b),	90
mounted sample (c).	
Figure 2.11 TESCAN MIRA3, SEM device (a), PAN, XRD phase analyzer (b).	91
Figure 2.12 SANTA, Universal Testing Machine (a), Al subsize tensile	92
specimen (b).	
Figure 2.13 BUEHLER, microhardness tester.	93
Figure 2.14 Autolab Potantio, corrosion rate measurement instrument.	94

xi

for zone D; b. SEM image of zone D-D; c, d, e and f are EPMA mapping	
analysis results of Al, Ti, Mn and Fe respectively.	
Figure 3.15 Microstructure appearance of zone E Fig. 3.8: a. optical image	111
for zone E; b.SEM image for zone E-E; c. EDS pattern of point scan for zone	
E-E	
Figure 3.16 High magnification SEM image near point C for: a. Fig. 3.9.b;b.	112
Figure 3.15.b.	
Figure 3.17 Shear force (N) vs. extension (mm) for various welding speeds:	113
a.6.67; b.5; and c.4 mm/s.	
Figure 3.18 Optical and SEM images of fractured samples under shear load	113
for various welding speeds: a,d 6.67; b,e 5; and c,f 4 mm/s.	
Figure 3.19 XRD patterns at the fracture surface interface of the Ti of Fig.	114
3.18.a.	
Figure 3.20 Shear stress values of: 1.joint at welding speed 4mm/s (76% pulses	115
overlap); 2.shear stress of Al bas metal; 3.tensile stress of Al bas metal.	
Figure 3.21 Microhardness test for different locations of Ti-Al laser welding	116
joint, for various welding speeds: a. 6.76 mm/s; b. 5 mm/s; c. 4 mm/s,	
(sample1,2and3) respectively.	
Figure 3.22 Shear force (N) vs. extension (mm) of sample 1 joint (welding	118
speed 6.67mm/s, 60% pulses overlap,): a. without PWHT; b. with PWHT; c.	
fractured PWHT sample; d. SEM image of fracture surface of PWHT sample	
Figure 3.23 XRD patterns at the fractured surface at interface of the Ti of Fig.	119
3.22.c	
Figure 3.24 The top and bottom surfaces appearance of Ti-Al laser welded	120
joints for: a,d. sample 4; b,e. sample 5; c,f. sample 6 respectively	
Figure 3.25 Weld cross sections of Fig. 3.24: a.section1-1; b.section2-2;	121
c.section3-3.	
Figure 3.26 Zone C in Fig. 3.25.b	122
Figure 3.27 Optical and SEM images of zones Fig. 3.25:a. SEM image of zone	123

xii

A; b,c. optical and SEM images of zone B respectively; d. optical image of	
zone D; e,f. optical and SEM images of zone E respectively	
Figure 3.28 EDS patterns of point scan of the yellow colored points of Fig.	123
3.27 a,c and f respectively	
Figure 3.29 Shear force vs. extension in addition to weld seam shape, at bottom	126
interface surface of Ti sheet for samples 4,5, and 6 respectively : a,d. sample 4;	
b,e. sample 5; and c,f. sample 6	
Figure 3.30 Optical and SEM images of fractured samples 4, 5 and	128
6respectively: a, d, g, for sample 4; b,e, for sample 5; and c,f, for sample 6	
Figure 3.31 XRD patterns of the fractured surfaces for samples: a.5; b.6	127
Figure 3.32 Shear stress values of: 1.sample 4; 2.shear stress of Al base metal;	128
3. tensile stress of Al base metal.	
Figure 3.33 Microhardness test for different locations of Ti-Al laser welding	129
joint, for samples No.; a.4; b.5 and c.6 respectively	
Figure 3.34 The top and bottom surfaces appearance of Ti-Al laser welded	131
joints for: a,d. sample 7; b,e. sample 8; c,f. sample 9 respectively	
Figure 3.35 Weld cross sections of Fig. 3.34: a. section 1, b. section 3, c.	131
section 5, d. section 2, e. section 4: a,b, and c (final pulses effect), d,e (normal	
overlapping pulses effect)	
Figure 3.36 Weld cross sections, optical image and SEM image of Fig. 3.35:	133
a, b and e optical image, SEM image and EDS point scan patterns of zone A in	
Fig. 3.35; c, d SEM image and EDS line scan patterns of Fig. 3.35.e.	
Figure 3.37 Equilibrium phase diagrams: a. Al-Si; b. Al-Mg [82].	134
Figure 3.38 Weld cross sections optical and SEM images of Fig.3.35: a, b and	135
c are optical and SEM images of zone B Fig. 3.35; d and e are optical and	
SEM images of zone C Fig.3.35; f and g are optical and SEM images of	
zone D Fig.3.35.	
Figure 3.39 EDS patterns point scan for the points presented in Fig. 3.38	136
respectively.	

Figure 3.40 Shear force vs. extension in addition to weld seam shape at bottom	139
interface surface of Ti sheet samples 7, 8and 9 respectively: a,d. sample 7; b,e.	
sample 8;and c,f. sample 9	
Figure 3.41 Optical, and SEM images of fractured samples 7,8and9:a. for	139
sample 7; b,d. for sample 8; and c, e, f. for sample 9	
Figure 3.42 XRD patterns of the fractured surfaces for samples 8and 9: a.8;	140
b.9.	
Figure 3.43 Shear stress values of: 1.sample 9; 2.shear stress of Al base metal;	140
3. tensile stress of Al base metal.	
Figure 3.44 Microhardness test for different locations of Ti-Al laser welding	141
joint, for samples 7, 8 and 9:a.7; b.8; c.9	
Figure 3.45 The top and bottom surfaces appearance of Ti-Al laser welded	144
joints for: a, c. sample 10; b,d. sample 11 respectively	
Figure 3.46 Weld cross sections of Fig. 3.45: a. section 1, b. section 2.	144
Figure 3.47Equilibrium phase diagrams of binary alloys: a. Al-Zr; b. Ti-Sc; c.	146
Ti-Zr systems	
Figure 3.48 Weld cross sections high magnification SEM images of Fig. 3.46:	148
a. zone A; b. zone B; c. zone C.	
Figure 3.49 Shear force vs. extension in addition to weld seam shape, at bottom	150
interface surface of Ti sheet for samples 10 and 11 respectively: a,c. sample	
10; b,d. sample 11	
Figure 3.50 Optical, images of fractured samples 10 and 11:a. for sample 10; b.	151
for sample 11.	
Figure 3.51 XRD patterns of the fractured surfaces for samples 10 Fig.50	151
Figure 3.52 Shear stress values of: 1.sample 11; 2.shear stress of Al base metal;	152
3. tensile stress of Al base metal	
Figure 3.53 Microhardness test for different locations of Ti-Al laser welding	153
joint, for samples: a.10; b.11	
Figure 3.54 The top and bottom surfaces appearance besides weld cross	155

section of Ti-Al laser welded joints for sample 12: a. tope surface b. bottom	
surface c. section 1	
Figure 3.55 High magnification SEM image and EDS line scan of line A Fig.	156
3.54.c: a.SEM image; b. EDS line scan	
Figure 3.56 Equilibrium phase diagram of binary alloys: a. Ti-Nb; b. Al-Nb	157
systems	
Figure 3.57 Shear force (N) vs. extension(mm)besides optical images for the	158
fractured sample 12:a. shear force (N) vs. extension(mm); b. weld interface	
surface of Ti sheet; c. fractured joint; d. weld interface surface of Al sheet.	
Figure 3.58 Shear stress values of:1.sample 12; 2.shear stress of Al base metal;	159
3. tensile stress of Al base metal	
Figure 3.59 Microhardness test locations of Ti-Al laser welding joint of	160
Figure 3.60 Applied electrode potential E(V) vs. current I(A) (polarization	162
curves) for samples:a.3; b.4;c.9 and d.11 respectively	
Figure 3.61 Overall shear force (N) results for samples:1.Sa.3; 2.Sa.4; 3.Sa. 9;	164
4.Sa.11; 5.Sa.12; 6. Al base	
Figure 3.62 Overall shear stress(MPa)results for samples :1.Sa.3; 2.Sa. 4; 3.Sa.	164
9; 4.Sa.11; 5.Sa.12; 6. Al base metal; 7.Al base metal tensile stress	
Figure 3.63 Overall polarization curves for samples.3, 4, 9 and d.11	165
respectively.	

LIST OF TABLES

Table 1.1 Absorptivity (A) of several metals at 1.06 and 10.6 µm at room	21
temperature	
Table 1.2 Appropriate filler addition to aluminum alloys	37
Table 1.3 Kinds, features, schematic representation, causes and	50
suppression or preventive procedures of main laser welding defects	
Table 1.4 Weldability of metal pairs	52
Table 1.5 Thermophysical properties of Ti and Al	60
Table 1.6 Material properties of titanium and titanium aluminide	61
Table 2.1 Standard and estimated chemical compositions of the materials	78

used in this study by wt.

Table 2.2 Physical properties of the materials used in this study	79
Table 2.3 Standard and estimated mechanical properties of the materials	79
used in this study	
Table 2.4 Laser welding parameters.	89
Table 3.1 Laser welding parameters	97
Table 3.2 Weight and atomic analysis of Al, Ti elements of zone A-A Fig.	104
3.9.b	
Table 3.3 Weight and atomic analysis of Al, Ti elements of zones B-B	107
and C-C in Fig. 3.11	
Table 3.4 Weight and atomic analysis of Al, Ti elements of zone E-E Fig.	111
3.15.b	
Table 3.5 Values of microhardness for different points that located in Fig.	117
3.21	
Table 3.6Weight and atomic analysis of Al, Ti and Si elements of Fig.	124
3.27.a,c and f respectively	
Table 3.7 Values of microhardness for different points that located in	129
Fig.3.33.	
Tables 3.8 Weight percent analyses of Al, Ti, Si and Mg elements for	137
EDS patterns scan of Fig.3.36. b, c and Fig. 3.38.c, e g respectively	
Table 3.9 Values of microhardness for different points that located in Fig.	142
3.44.	
Tables 3.10 Weight percent analysis of Al, Ti Sc and Zr elements for EDS	149
patterns scan of Fig. 3.48.a,b and c respectively.	
Table 3.11 Values of microhardness for different points that located in	153
Fig. 3.53.	
Tables 3.12 Weight percent analysis of Al, Ti and Nb elements by EDS	156
patterns line scan that presented in Fig. 3.55.	

Table 3.13 Values of microhardness for different points that located in160Fig.3.59AWSAmerican welding society

Table 3.14 Values of Ecorr., Icorr., polarization resistance cathodic,163anodic, reactions and corrosion rate for samples 3,4,9 and 11 respectively.165Table 3.15 Values of corrosion rate and corrosion rate efficiencies for165samples 3, 4, 9 and 11 respectively165

ABBREVIATIONS

BM	LEST GEASYMBOLS
CW	Continues mode of operation (Continues wave)
EBW	Absolute temperature K Electron beam welding
EDS T _e	Electron lattice temperature K Energy dispersive spectrometer
EM	Electromagnetic radiation
EMPA	Electron microprobe analysis
EPPD	Effective peak power density
FZ	Fusion zone
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HAZ	Heat affected zone
IMP	Intermetalic phases
IR	Infrared radiation
INLC	Iranian national laser center for science and technology
Nd:YAG	Neodymium-yttrium aluminum garnet
PAW	Plasma arc welding
PRR	Pulse repetition rate
PRT	Pulse repetition time
R	Reflected energy %
SAW	Submerge arc welding
SEM	Scanning electron microscope
SUT	Sharif university of technology
Т	Energy transmitted %
TEM _{xx}	Transverse electromagnetic mode
UV	Ultra-violet
XRD	X-ray diffraction

To	Ambient temperature	Κ
P _{av}	Average power	W
P _D	Vapor pressure	Pa
Ру	Plasma pressure	Pa
P _{ab}	Ablation pressure	Pa
P_{γ}	Surface tension pressure	Pa
P _{hs}	hydrostatic pressure	Pa
P_{hd}	Hydrodynamic pressure.	Pa
Ea	Average thermal input per unit area	J/m^2
M^2	Beam quality factor	
T_{b}	Boiling temperature	K
k	Boltzmann constant	J/K
T_d	Degradation temperature	K
ρ	Density	Kg/m ³
DC	Duty cycle	
t _e	Electron cooling time	ps
3	Emissivity	
$E_{\lambda b}$	Emitted energy by a blackbody	J
E_{λ}	Emitted energy by real object	J
k	Extinction coefficient	
$F^{\#}$	F number	
f	Focal length	mm
Ι	Intensity	W/cm ²
Z	Intensity attenuation distance beneath a surface	μm
L_v	Latent heat for vaporization	J/kg
t_l	Lattice heating time	ps
I_o	Maximum intensity	W/cm ²
T_{m}	Melting temperature	Κ
N	Number of overlapping spots for one joint spot	n spots

$\mathbf{P}_{\mathbf{p}}$	Peak power	kW
h	Planck constant	J.s
τ	Pulse duration	ms
E _{pulse}	Pulse energy	J
r	Radial distance across the pulse spot	μm
L	Raleigh length	mm
g	Rate of energy per unit time per unit volume	$J/m^3.s$
D	Raw beam diameter	mm
ω _{real}	Real spot size	mm
$A_{ m o}$	Initial area	mm^2
$A_{ m f}$	Final area	mm^2
v	Scanning speed	mm/s
С	Specific heat	KJ/Kg. K
C _e	Electron specific heat	KJ/Kg. K
C_l	Lattice specific heat	KJ/Kg. K
c	Speed of light	m/s
ω	Spot size	mm
PER	Spots overlapping percentage	%
K _B	Stefan-Boltzmann's constant	$J/m^2.K^4$
K	Thermal conductivity	W/m. K
α	Thermal diffusivity	m^2/s