BEHAVIOR AND RELIABILITY OF RADIATION-PROCESSED, SINGLE-MODE LENSED-FIBER AFFIXING JOINTS IN PUMP LASER PACKAGING

TAN CHEE WEI

DOCTOR OF PHILOSOPHY
CITY UNIVERSITY OF HONG KONG
NOVEMBER 2006
Behavior and Reliability of Radiation-Processed, Single-Mode Lensed-Fiber Affixing Joints in Pump Laser Packaging

Submitted to
Department of Electronic Engineering
in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

by

Tan Chee Wei
陳志偉

November 2006
二零零六年十一月
ABSTRACT

For the packaging of a pumped laser in a 14-pins butterfly package, i.e. a 980nm pump laser, the most crucial assembly step is the fiber-to-laser diode coupling and fixing. Relatively, the use of laser welding as the fixing method offers several advantages, strong joint strength, short process time and less contamination. The first part of this study reports on laser welds formed by various physical schedules corresponding to various incident beam energies (IBE); laser welding process characteristics, and the behavior of laser-welded joints between pure nickel (Ni200) weld clips and Kovar™ base metal under various mechanical loadings, i.e. shear and fatigue in shear were characterized. The mechanical stability of fiber-solder-ferrule (FSF) joints under temperature cyclic loading is discussed. Four different thicknesses of solder filler of FSF joints were examined. In the second part of this thesis, the effectiveness of a pulsed laser beam and soft beam energy as a heat source for an optimum solder joint that fixes a lensed-fiber permanently on a Ni/Au-plated substrate are also reported.

The penetration depth and fusion zone of laser spot welds was found to be a complicated function of laser pulse energy, power intensity, and beam diameter. The weld strength was found to be dependent on the overlapping area between the two joining materials which strongly depends on the charge voltage, pulse width, input power, and size of the focal spot to the rate of energy input to the workpieces. The pulse width has a dominant effect on the weld width while the charge voltage dominates the depth of penetration and thus increases the absorbed power density. Surface roughness, \( R_a \), has an influence on the fraction of energy absorbed, \( A \), and therefore, affects the penetration depth.
From the results of a simple mathematical model, a higher peak temperature is achieved when the lateral distance is set closer to the heat source, and it reaches a peak temperature in a shorter time. When the lateral distance decreases, the peak temperature increases and the thermal gradient decreases. The heat-affected zone (HAZ) that was produced by the selected incident beam energy (IBE) range is very thin. A larger grain size was obtained in the center of the weld pool that has a lower thermal gradient and a smaller grain size was observed near the cooled wall that has a higher thermal gradient, which is the base metal in this case. A larger number of grains were obtained for weld pools that were produced using a lower IBE. In the fusion zone, a cellular structure and/or an elongated cellular structure were observed due to the effect of the solidification rate on the growth mechanism. A lower temperature gradient will result more often in a cellular structure while a columnar structure is concentrated in regions with a higher temperature gradient, near to the base metal.

A Nd:YAG laser source of wavelength 1064nm was used to weld 1.0x1.0x0.2mm Ni200 pieces onto a Kovar™ substrate by a single pass spot weld. These samples were then subjected to shear tests. The maximum shear force required to break a joint ranged between 90-95N, 70-75N, and less than 45N when welded by 380V, 360V and 340V, respectively. The shear strength very much depends on the spot weld diameter and beam penetration depth. In general, a higher pulse width at the same energy increases the joint diameter, reduces penetration, i.e., produces conduction welding and thus reduces the shear strength. The condition of dimples observed in the fracture surface after shear tests provides an important indication on the properties of the weld joints.

Three different surface conditions of Kovar™-based substrates, i.e., bare Kovar™, Au plated and Ni plated have been employed to form laser-welded joints with pure Ni weld
clips. Shear fatigue cyclic tests were performed on four weld spots that joined Ni200 saddle shape weld clips onto the Kovar™ base metal. The effects of various welding conditions, i.e., pulse width and charge voltage on the fatigue life of the laser-welded joints were evaluated. It was found that the fatigue life mostly depends on the cross sectional area of the weld joint for the same surface treatment, and that depends on the pulse width and charge voltage. In general, Ni plating and Au plating drastically lower the fatigue life. The fatigue life for the weld formed using the selected welding condition ranges from 1225 to 1497 cycles for a bare Kovar™ substrate while it ranges from 24 to 235 cycles for metallized surfaces. The surface condition of a fracture surface after a shear fatigue test provides a direct indication on the crack propagation rate. The fracture surfaces of these samples were observed to be smoother and showed less plastic deformation, which suggested that these joints were brittle. In addition, a shallow sunken fracture mode with more Ni-particles on the fracture surface was observed at the fracture surface of the plated substrates suggesting that these joints had fractured underneath the Ni-plated layer. Important mechanical characteristics of these joints, i.e., constants $A'$ & $K$, $\log N_{50\%}$ and $\mu_N$ were estimated. These values are useful for modeling the fatigue characteristics of laser-welded joints and for the prediction of fatigue life.

In this study, four different thicknesses of solder filler of FSF joints were examined. By using a finite element method (FEM), their equivalent creep strains of the eutectic lead-tin solder were compared. The joints were subjected to 5 cycles of a temperature cycling test. The applied temperature profile consisted of a cycle of 15 minutes exposure to a high temperature 150°C, and then 15 minutes exposure to a low temperature of -65°C and the ramping time was about 60 seconds. It was found that the thicker solder filler would be subjected to a larger equivalent creep strain than the thinner solder filler. The
discussion and argument surrounded the vertical shift (Y-axis) because it is relatively more sensitive to temperature and has more effects to coupling loss. Modeling and experimental results showed that 0.5 mm is the best inner diameter of a ferrule to provide the lowest displacement and thus the lowest power lost under temperature cycles.

PbSn solder was laser-soldered onto solder pads coated with a typical Ni/Au metallization. The results show that the morphology of the microstructure and intermetallic formation is strongly influenced by the laser input power. Overall, well-spread solder joints were obtained at higher laser power inputs, while poor wetting was generally observed at lower power levels with very irregular joint strengths. With sufficient laser input energy, Au dissolved into the molten solder completely, as needle-like AuSn$_4$ intermetallic particles. This exposed the underneath Ni-metallization which then formed a Ni$_3$Sn$_4$ intermetallic layer with Sn that provided the actual joint integrity. In aged samples, an AuSn$_4$ intermetallic layer re-deposited at the joint interface and formed Au$_{0.5}$Ni$_{0.5}$-Sn$_4$ with Ni from the metallization underneath. The Au$_{0.5}$Ni$_{0.5}$-Sn$_4$ intermetallic layer grew thicker with the aging time. Higher temperatures caused Au$_{0.5}$Ni$_{0.5}$-Sn$_4$ intermetallic spalling which moved into the bulk solder, and appeared as a mixture of globular and rod structures. After 1000 hours of aging, Ni$_3$Sn$_4$ intermetallic was also detected in the bulk solder together with Au$_{0.5}$Ni$_{0.5}$-Sn$_4$ intermetallic. The microstructure of bulk solders slowly changed from a degenerate structure into a lamellar-like structure, and continuous Pb-rich colonies were observed at the joint interface. In the meantime, changes in the microstructure and growth of intermetallic layers that were due to the thermal history significantly modified the shear strength of these solder joints.
Solders, i.e., Pb37Sn, Au20Sn and Sn3.5Ag0.5Cu (SAC) [wt%] were evaluated for a fluxless application using a soft beam heating system. The microstructures of the solder joints have been examined using SEM, in order to understand the response of these solder materials to the focused white light. Obviously, the exposure time has a greater effect on the soldering temperature before reaching the peak temperature which is determined by the power. A power setting of 40W can reach approximately 340°C; 30W can reach about 310°C while 25W can easily reach 260°C. In general, a soldering temperature higher than the melting temperature is required to form well wetted solder joints for fluxless applications. However, too high an input thermal energy may result in premature aging for the cases of Pb37Sn and SAC, and lateral cracks for the case of Au20Sn. The thermal cracks and voids observed in Au20Sn solder joints were attributed to the fact that the soft beam heating profile does not suit the AuSn preform. Out of these 3 solder types, SAC demonstrated just the right response to the soft beam, i.e, good wetting, a fine and homogeneous structure, and no cracks or other visible failures.
Table of Contents

Abstract i
Declaration vi
Acknowledgements vii
Table of Contents viii
List of Figures xi
List of Tables xv
Abbreviations xvi
Symbols xvii

Chapter 1 Introduction
1.1 Overview on Photonic Packaging 1
   1.1.1 Challenges in pump laser packaging 1
1.2 Lensed-fiber Affixing Technologies 3
   1.2.1 Pulsed Nd:YAG laser welding technology 3
   1.2.2 Distinctive soldering technologies 4
1.3 Objectives 6

Chapter 2 Literature Review
2.1 Brief History of Optical Communication 7
2.2 LASER 9
   2.2.1 Solid-state laser (Nd:YAG) 11
   2.2.2 Semiconductor laser (pumped laser) 11
2.3 Pulsed Nd:YAG Laser Welding Technique 13
   2.3.1 Models 16
   2.3.2 Materials 18
   2.3.3 Microstructural analysis 20
   2.3.4 Mechanical tests 22
2.4 Fiber-Solder-Ferrule (FSF) Joints 24
   2.4.1 Modeling 27
      2.4.1.1 Equivalent creep strain 27
      2.4.1.2 Materials and properties 28
2.5 Distinctive Soldering Technologies 29
   2.5.1 Laser soldering 30
   2.5.2 Soft beam heating system 32
   2.5.3 Thin-film micro-heater 34

Chapter 3 Experimental Philosophy
3.1 Process Characterization 36
   3.1.1 Procedure characterization 37
   3.1.2 Microstructural analysis 38
   3.1.3 Fillet weld using Au-plated ferrule 39
3.2 Mechanical Tests 39
   3.2.1 Shear testing 39
   3.2.2 Shear fatigue cyclic test 40
3.3 Characterization on FSF Joints 41
   3.3.1 Design of experiments (DOE) 41
   3.3.2 FEM modeling 42
   3.3.3 Effect of laser beam on alignment shift 44
3.4 Pulsed Laser Soldering 45
Part A – Characterization on Laser Welding Technology

Chapter 4 Characterization of Pulsed Laser Spot Welding Technology
4.1 Introduction 51
4.2 Process Characterization 51
4.2.1 Modeling 57
4.3 Weld Strength 61
4.4 Influence of Laser Beam Pulse Heating & Rapid Solidification 64
4.5 Structure of the Fe-Ni-Co Alloys 65
4.6 Effect of Au-Plating Layer to the Microstructure 71
4.7 Summary 73

Chapter 5 Mechanical Properties of the Pulsed Laser Spot Welded Joints
5.1 Introduction 75
5.2 Shear Test 76
5.3 Shear-Fatigue Test 82
5.4 Summary 95

Chapter 6 Effect of Solder Filler Thickness on The Mechanical Stability of Fiber-Solder-Ferrule Joint
6.1 Introduction 97
6.2 Effect of Solder Filler Thickness 97
6.2.1 Equivalent creep strain distribution in a FSF joint 97
6.2.2 Fiber position 103
6.2.3 Displacement 107
6.2.3.1 Effect of laser beam power and focus position 107
6.2.3.2 Effect of temperature cycling 109
6.3 Summary 112

Part B – Eliminate Ferrule By Using Distinctive Soldering Technologies

Chapter 7 Characterization of Pulsed Laser-Soldered Joints
7.1 Introduction 113
7.2 Effect of Lasing Parameters on Wetting and Spreading 113
7.3 Effect of Lasing Parameters on Solder Microstructure 115
7.4 Effect of Lasing Parameters on Shear Strength 118
7.5 Reliability Performance 120
7.5.1 Effects of aging tests on shear strength 120
7.5.2 Effects of aging tests on solder joint integrity 123
7.6 AuSn Pulsed Laser-Soldered Joint 129
7.7 Effect of Cyclic Temperature to Alignment Position Shift 131
7.8 Summary 138

Chapter 8 Distinctive Soldering Technologies
8.1 Introduction 141
8.2 Soft Beam Heating System 141
  8.2.1 Characterization on the temperature profile 141
  8.2.2 Characterization on the soft beam-soldered joints 143
8.3 Thin-Film Micro-Heater or Resistor Chip 149
  8.3.1 Performance of the heaters 150
8.4 Summary 152

Chapter 9 Conclusions and Suggestions for Future Work
9.1 Conclusions 153
9.2 Suggestions for Future Work 160
  9.2.1 Thin-film heater substrate 160
  9.2.2 Direct fiber soldering 162
  9.2.3 Glass solder preform 163

References 165

Appendices
Appendix A – Publication list 176
Appendix B – Presentation material for oral examination 179
List of Figures

Fig. 1.1: A schematic diagram of a 980nm pump laser in a 14-pin butterfly package 3
Fig. 1.2: A schematic diagram of the sub-assembly in a butterfly package where the lensed-fiber is fixed by laser spot welding technology 4
Fig. 1.3: A schematic diagram of a 980nm pump laser in a butterfly package where the lensed-fiber was fixed by a soldered joint 5
Fig. 2.1: The combination of spontaneous emission first, and then stimulated emission causes the laser to "lase," which means it generates a coherent beam of light at a single frequency (Farlex, Inc., 2005) 10
Fig. 2.2: A schematic diagram of the optical fiber affixing configuration in a pumped laser 14
Fig. 2.3: Simulated coupled power efficiency and its sensitivity vs. fiber position (Yang et al., 2002) 25
Fig. 2.4: A schematic diagram of a soldered joint that fixes the lensed-fiber permanently on the submount 33
Fig. 2.5: A schematic diagram of the principle of Soft Beam Heating System 34
Fig. 2.6: Schematic diagram of a improved version of the thin-film heater; diagonal area refers to a) Nichrome, b) heat conducting electrically insulating layer, and c) Au layer (dimension in mm) 35
Fig. 3.1: Experimental setup for a) shear test and b) shear fatigue cyclic test 40
Fig. 3.2: Schematic diagram of the definition of misalignment of the fiber to the center of the ferrule, $\Delta X$ and $\Delta Y$ 42
Fig. 3.3: Temperature profile of the temperature cycling test 43
Fig. 3.4: A schematic diagram to show the lensed-fiber tip from a) side view, and b) front view 44
Fig. 3.5: Position and sequence of the laser welding 45
Fig. 3.6: A schematic diagram of a thin-film micro-heater 50
Fig. 4.1: Relationship between pulse width and energy detected in the output beam 52
Fig. 4.2: Energy and power density determined at various input powers 53
Fig. 4.3: Beam penetration depth and weld bead width measured at various IBEs 54
Fig. 4.4: Relationship of keyhole depth and weld pool depth with the weld pool diameter 54
Fig. 4.5: The $45^\circ$ angle of the laser beam with the target surface induced a) weld pool and keyhole at high power density ($13.5 \times 10^5 \text{W/cm}^2$), b) weld pool and shallow keyhole penetration at lower power density ($4.2 \times 10^5 \text{W/cm}^2$) 55
Fig. 4.6: Power density vs a) charge voltage at 3ms and b) pulse width at 350V 56
Fig. 4.7: Transverse-view of the weld pool and keyhole produced by a) 380V @ 3ms, b) 340V @ 8ms and c) 340V @ 3ms 56
Fig. 4.8: Relationship of the weld pool diameter with distance from the focal length  
Fig. 4.9: Model prediction of the thermal cycle at a point (r=0.1 mm) on the surface of the autogenous laser weld  
Fig. 4.10: Model prediction of the thermal cycle at points on the surface of the weld pool in a laser weld (absorptivity taken as 0.7 and IBE as 0.5 J/cm²)  
Fig. 4.11: Experimental data for the HAZ width as a function of incident beam energy. The model prediction, obtained using an absorptivity of 0.7 is shown in solid line.  
Fig. 4.12: Peak temperature as a function of incident beam energy (IBE) for a Kovar™ metal alloy at a point, r = 1.0 mm from the heat source  
Fig. 4.13: Shear force vs displacement curves determined from welds produced at various power densities  
Fig. 4.14: Fractographs of sheared joints on the rough substrate surface which were welded at a) 13.4 x 10⁵ W/cm², b) 9.0 x 10⁵ W/cm², c) 7.0 x 10⁵ W/cm², and d) 2.8 x 10⁵ W/cm²  
Fig. 4.15: Shear force of the welded joints produced at various power densities for an EDM wire cut surface finish and a polished surface  
Fig. 4.16: Effect of beam position from the optimal location on the weld load  
Fig. 4.17: Cross-sectioned views of the etched laser welds by IBEs of a) 0.8 J/cm², b) 0.5 J/cm², c) 0.35 J/cm², d) 0.3 J/cm², e) 0.2 J/cm², and f) 0.1 J/cm²  
Fig. 4.18: SEM micrographs of the morphology of cross-sectioned laser welds by IBEs of 0.5 J/cm² at a) keyhole-HAZ interface, b) weld pool-base metal interface, and c) center of the weld pool  
Fig. 4.19: SEM micrographs of the morphology of a laser weld induced by IBE of 0.3 J/cm² at a) top of weld pool, b) weld pool-base metal interface, and c) center of the weld pool  
Fig. 4.20: Cross-sectioned laser weld induced by IBE of 0.2 J/cm² at a) top of weld pool, b) weld pool-base metal interface, and c) center of the weld pool  
Fig. 4.21: a) Cellular structure obtained due to the lower thermal gradient at the center of fusion zone and b) combination of elongated cellular and columnar structure obtained due to higher thermal gradient near the base metal  
Fig. 4.22: Cross-section views of a) a fillet weld, b) shoulder of the weld clip, c) Au-rich HAZ, & d) enlarged fusion zone of weld clip shoulder  
Fig. 5.1: Shear force vs displacement for joints welded at a) 380V b) 360V at 7ms, 5ms and 3ms pulse widths and c) 340V at 7ms and 5ms  
Fig. 5.2: Maximum shear force and shear strength for joints formed using various welding conditions (see Table 5.1)  
Fig. 5.3: Fractographs of Ni200 laser welded joints after shear tests for samples that were welded by conditions a) Run 1-2, b) Run 1-3, c) Run 1-5, d) Run 1-6, e) Run 1-7, f) Run 1-8 (see table 5.1)
Fig. 5.4: Enlarged views of fractographs for a) Run 1-3 b) Run 1-6 c) Run 1-8 and d) Run 1-9 (see Table 5.1)  
82

Fig. 5.5: Fatigue lifetime as Wöhler curves for a) Runs 1-3 & b) Runs 4-6  
85

Fig. 5.6: Log($\sigma_a$) versus Log($N_f$)  
86

Fig. 5.7: Fractographs of welds after fatigue shear tests for a) Run 1, b) Run 2, c) Run 3, d) Run 4, e) Run 5 and f) Run 6. Location X5, X6 & X7 are the locations of interest in the EDX analysis (see Table 5.4)  
88

Fig. 5.8: Enlargements of fracture surfaces of samples from a) Run 1, b) Run 2, c) Run 3, d) Run 4, e) Run 5, and f) Run 6  
90

Fig. 5.9: a) Transgranular fracture surface that appears with fine fibrous dimples, b) weld surface with fine cellular sub-structure of samples from Run 2. Location X4 is the spot in the EDX analysis given in Table 5.4.  
91

Fig. 5.10: Locations of X1 and X2 EDX analysis given in Table 5.4 for sample from Run 4  
93

Fig. 6.1: Modeling data of equivalent creep strain on the filler with different inner diameters of ferrule.  
100

Fig. 6.2: Equivalent creep strain contours of the solder filler when the inner diameter of ferrule was 0.2mm (only solder filler is shown)  
100

Fig. 6.3: Equivalent creep strain contours of the solder filler when the inner diameter of ferrule was 0.4mm (only solder is filler shown)  
101

Fig. 6.4: SEM cross-section micrographs and its equivalent EDX mapping images of the construction of a FSF joint. The magnitudes of shift were measured in the SEM as well. (Yellow: Si; Blue: Pb; Green: Ni; Red: Fe)  
104

Fig. 6.5: X-Y scatter plot of the total shift away from the center of a ferrule established prior to soldering  
105

Fig. 6.6: Magnitude of shift versus temperature. Arbitrary zero is set at 25°C  
106

Fig. 6.7: Coupling efficiency at various lensed-fiber positions  
107

Fig. 6.8: Displacement against time (U1: horizontal, U2: vertical) when the inner diameter of ferrule was 0.2mm  
110

Fig. 6.9: Displacement against time (U1: horizontal, U2: vertical) when the inner diameter of ferrule was 0.4mm  
110

Fig. 6.10: Displacement of the optical fiber at high temperature, 150°C (only optical fiber is shown)  
111

Fig. 6.11: Displacement of the optical fiber at low temperature, -65°C (only optical fiber is shown)  
111

Fig. 7.1: Cross-sectional views of solder joints at time zero for various lasing parameters: a) Run 1, b) Run 2, c) Run 3, d) Run 4, e) Run 5, f) Run 6, g) Run 7 & h) Run 8  
117

Fig. 7.2: Shear force and strength (approximate) versus various lasing parameters  
119

Fig. 7.3: Shear force and strength (approximate) vs aging time  
120

Fig. 7.4: Solder joints aged for 100 hours formed by various lasing parameters: a) Run A, b) Run B, c) Run C & d) Run D (see Table
7.1) Solder joints aged for 250 hours formed by various lasing parameters: a) Run A, b) Run B, c) Run C & d) Run D

Fig. 7.5: Solder joints aged for 250 hours formed by various lasing parameters: a) Run A, b) Run B, c) Run C & d) Run D

Fig. 7.6: Solder joints aged for 750 hours formed by various lasing parameters: a) Run A, b) Run B, c) Run C & d) Run D

Fig. 7.7: Solder joints aged for 1000 hours formed by various lasing parameters: a) Run A, b) Run B, c) Run C & d) Run D

Fig. 7.8: a) Au-Ni-Sn and b) Ni₃Sn₄ intermetallic layer thicknesses versus aging test time (For an explanation of A to D, see Table 7.1)

Fig. 7.9: A transverse view of a sectioned Au-Sn pulsed-laser soldered joint

Fig. 7.10: Transverse section view of an as-soldered Au-Sn pulsed-laser soldered joint at a) at the fiber-solder interface, b) solder fillet-substrate interface

Fig. 7.11: Transverse view of reflow-soldered AuSn where a) Au-rich islands in a dendritic structure are observed and b) lamellar structure is observed in the enlarged view of the joint

Fig. 7.12: Temperature profile of the thermal cyclic test

Fig. 7.13: Equivalent creep strain at the solder joint with different fillet diameters

Fig. 7.14: Equivalent creep strain contour of solder joint when the solder fillet is 0.5mm

Fig. 7.15: Maximum displacement of solder joint with different fillet diameter at a) -40°C, and b) 125°C (horizontal: X-axis; vertical: Y-axis; distance between lensed-fiber and laser chip: Z-axis)

Fig. 7.16: Horizontal (X-axis) displacement against time when the fillet diameter is 0.5mm

Fig. 7.17: Vertical (Y-axis) displacement against time when the fillet diameter is 0.5mm

Fig. 7.18: Z-axis displacement against time when the fillet diameter is 0.5mm

Fig. 8.1: Measured temperature profiles of solder pad at various soft beam parameters

Fig. 8.2: Cross-sectional views of the microstructures of PbSn solder joints a) 40W for 40s, b) 25W for 40s & c) 25W for 30s

Fig. 8.3: Cross-sectional views of as-soldered Au80Sn solder joints a) 40W for 40s, b) 40W for 60s, c) 40W for 90s, d) 40W for 80s and e) 30W for 90s

Fig. 8.4: Cross-sectional views of as-soldered Sn-Ag-Cu solder joints a) 40W for 40s, b) 40W for 20s, c) 25W for 40s, d) 25W for 60s, e) 30W for 30s, and f) 40W for 30s

Fig. 8.5: Temperature profile versus time of a) sample 1 with a resistance of 3.7ohm and b) sample 2 with a resistance of 2.5ohm

Fig. 8.6: Comparison of temperature profiles (T-V) of a) sample 1 and b) sample 2 at 10s
List of Tables

Table 2.1: Summary of the chemical composition of Ni 200 and Kovar™ (High Temp Metals Website) 19
Table 2.2: A table shows the mechanical and thermal properties of Ni 200 and Kovar™ (High Temp Metals Website) 19
Table 2.3: Creep constants of solders (Hong, 1998) 28
Table 2.4: Physical and mechanical properties of the selected materials (Cheng et. al, 2001; Hong 1998; Tseng & Chang, 2003) 29
Table 3.1: Summary of the parameter settings for each physical schedule. The pulse width was fixed at 3.0ms 36
Table 3.2: Design of Experiment 37
Table 3.3: Summary of the shear fatigue cyclic tests data 40
Table 3.4: Selected configurations for FSF joints 43
Table 3.5: Experimental design of the charge voltage and pulse width of the laser source 46
Table 3.6: Design of Experiment (DOE) 49
Table 3.7: Summary of the solder materials properties 49
Table 3.8: Design of Experiment (DOE) 49
Table 4.1: Chemical composition of the Fe-Ni-Co alloy 53
Table 5.1: Summary of the shear test data 78
Table 5.2: Summary of the shear fatigue cyclic tests data 83
Table 5.3: Chemical Composition Analysis on fracture surface, in wt% 86
Table 5.4: Chemical Composition at selected locations, in wt% 92
Table 5.5: Summary of the secondary data 94
Table 5.6: Displacement against Von Mises stress in the fiber with different diameters of solder filler at high temperature, 150°C 103
Table 6.1: Measured shift of the lensed-fiber at X & Y -axes 108
Table 6.2: Experimental design of the charge voltage and pulse width of the laser source 114
Table 7.1: EDX quantitative elemental analysis of intermetallic layers at the bonding interface 115
Table 7.2: Design of experiments (lasing conditions) and results of the failure mode in shear tests 119
Table 7.3: Shear test failure modes of aged samples 122
Table 7.4: Growth constants, k 128
Table 7.5: Von Mises stress recorded form the simulation for the selected fillet diameters 138
Table 8.1: Summary of the metallization thicknesses obtained by XRF 149
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>Anti-Reflection</td>
</tr>
<tr>
<td>AST</td>
<td>Accelerated Stress Testing</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DFB</td>
<td>Distributed Feedback</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of Experiment</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium-Doped Fiber Amplifier</td>
</tr>
<tr>
<td>EDX</td>
<td>Energy Dispersive X-Ray Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FP</td>
<td>Fabry Perot</td>
</tr>
<tr>
<td>FSF</td>
<td>Fiber-Solder-Ferrule</td>
</tr>
<tr>
<td>HAZ</td>
<td>Heat-Affected Zone</td>
</tr>
<tr>
<td>HCF</td>
<td>High Cycle Fatigue</td>
</tr>
<tr>
<td>IBE</td>
<td>Incident Beam Energy</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LASER</td>
<td>Light Amplification By Stimulated Emission of Radiation</td>
</tr>
<tr>
<td>LCF</td>
<td>Low Cycle Fatigue</td>
</tr>
<tr>
<td>LD</td>
<td>Laser Diode</td>
</tr>
<tr>
<td>MASER</td>
<td>Microwave Amplification By Stimulated Emission of Radiation</td>
</tr>
<tr>
<td>Nd</td>
<td>Neodymium</td>
</tr>
<tr>
<td>PWS</td>
<td>Post-Weld Shift</td>
</tr>
<tr>
<td>RE</td>
<td>Rare Earth</td>
</tr>
<tr>
<td>SAC</td>
<td>Sn-Ag-0.5Cu Solder Alloy</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>S-N</td>
<td>Stress-Strain Curve</td>
</tr>
<tr>
<td>TO</td>
<td>Transistor Outline</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>XRF</td>
<td>X-Ray Fluorescence Spectroscopy</td>
</tr>
<tr>
<td>YAG</td>
<td>Yttrium Aluminum Garnet</td>
</tr>
</tbody>
</table>
Symbols

b - Shape parameter (Weibull Slope)
c - Heat capacity
e - Base of natural logarithms
k - Growth constant
n' - 10, hardening index
n - Number given by the reciprocal of the negative gradient of the log-σ/log-
    N_f in the Wöhler curve (S-N curve) of the material
r - Lateral distance from the heat source
t - Time
x - Value of the random variable (number of cycles to failure, N_f)
A - Absorptivity
A' - Constant
A, B - Material constants
E - Young modulus
G - Thermal gradient
G/ν - Solidification parameter
K - Factor characteristic of the weld joint
N - Stress exponent
N_f - Fatigue life
Q - Activation energy (J/mole)
R_a - Surface roughness
R - Universal gas constant (8.314 kJ/kg mole K)
R_o - Reflectivity of a smooth surface
T - Absolute temperature (K)
T_o - Ambient temperature
T_m - Melting temperature of the welded metal
T_1 - Welding temperature
\( \alpha \) - Coefficient of thermal expansion
\( \beta \) - 0.001
\( \delta \) - IMC thickness
\( \varepsilon \) - Uniaxial strain
\( \dot{\varepsilon}^{cr} \) - Uniaxial tensile creep strain (1/S)
\( \gamma \) - 3/7
\( \kappa \) - Thermal conductivity
\( \lambda \) - Wavelength
\( \mu_N \) - Mean lifetime
\( \nu \) - Velocity of the solidification front
\( \theta \) - Scale parameter (Characteristic Value)
\( \rho \) - Density
\( \sigma \) - Applied uniaxial tensile stress (MPa)
\( \sigma_a \) - Stress amplitude
\( \sigma_{op} \) - Stress range under normal cycling conditions
\( \sigma_T \) - Stress range during the accelerated cycling test
\( \sigma_y \) - Yield stress
\( \sigma_{0.7} \) - Uniaxial stress at a secant modules of 0.7E