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Study on the weldability of stainless steel fabricated by powder metallurgy and metal injection molding for optoelectronic packages

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Abstract. To reduce the cost of optoelectronic modules, powder metallurgy (PM) and metal injection molding (MIM) are employed to fabricate metal housings for optoelectronic packages. During the laser welding of PM steel, the rising gas pressure pushes the molten metal out of the welding regions, resulting in weak and unstable joints. Metal parts fabricated by the MIM method provide good weldability, shape complexity, low cost, and long-term reliability. By using the MIM method, defect-free welding joints and postwelding-shifts of less than 1 μm are achieved, and the optoelectronic packages are reliable. Employment of MIM not only gives optoelectronic module designers more design flexibility due to the advantage of shape complexity, but also makes low-cost triple-directional optoelectronic modules realizable. [DOI: 10.1117/1.2335883]

Subject terms: laser welds; optoelectronic packages; metal injection molding; fiber; bidirectional transmission.

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1 Introduction

The successful introduction of low-cost bidirectional or even triple-directional optoelectronic modules is the key for fiber to the home (FTTH) to be widely used, and the primary cost arises from packaging the laser. To reduce the cost of optoelectronic modules, a number of approaches such as diffractive optical elements, passive alignment, and planar waveguide circuits[1–3] have been proposed. Among these approaches, laser welding techniques for optoelectronic packages offer lots of advantages, such as high joint strength to welding size ratio, high volume and high speed production, submicron accuracy, and good repeatability.[4–9]

The bodies of laser packages are typically categorized into two styles: box type and cylindrical type.[4,10] The box and cylindrical-type optoelectronic packages dominate high-performance communication systems and low-cost markets, respectively. The box-type package allows more space for a thermoelectric cooler and multiple components to achieve high speed, high power output, and high reliability. The cylindrical-type package based on transistor outline (TO)-Can laser diode package is used where the fabrication cost is important and the performance requirement is not so high. Recently, FTTH systems have delivered video, voice, and data to consumers on one fiber with 1310 nm in one direction and 1490 and/or 1550 nm in the other. However, this bidirectional and triple-directional data transmission of FTTH systems requires the transformation of cylindrical-type packages into box-type packages, because more space is needed to accommodate more wavelength division multiplexing (WDM) filters and lenses, as shown in Fig. 1. This transformation results in increased number and cost of metal parts, which is contradictory to the low-cost market. In addition, machining accuracies of metal parts are very critical to the yields of the laser welding process. Although the conventional machining method can make metal parts with a box shape and accurate dimensions, the cost is too high.

Despite numerous studies on improving the performance of the box-type optoelectronic packages recently,[10–12] only limited information is available for designing and fabricating high-yield, high-performance, and low-cost bidirectional and triple-directional optoelectronics packages. In this study, conventional powder metallurgical (PM) and metal injection molding (MIM) methods for optoelectronic packages are proposed. The PM method shows less production cost and high accuracy, but it provides less shape complexity and low mechanical strengths.[13] The MIM method offers five features: low production cost, shape complexity, tight tolerance, applicability to several materials, and high mechanical strength.[14] Therefore, employing the MIM method not only reduces the number of metal parts but also

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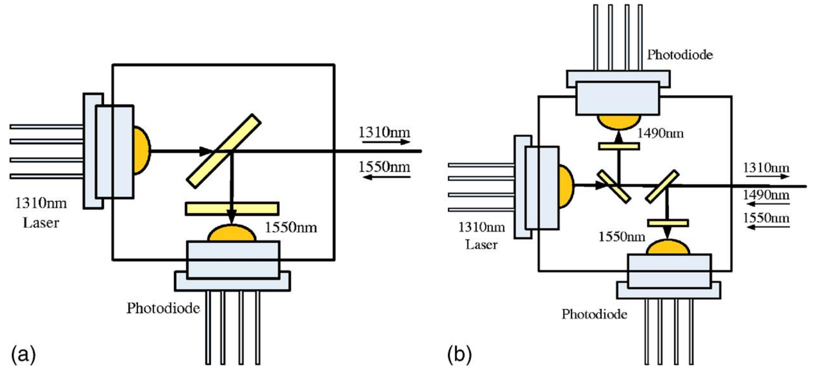

Fig. 1 The box-type packages allow more room for WDM filters, lenses, and the associated metal parts. (a) Illustration of bidirectional optoelectronic package. (b) Illustration of triple-directional optoelectronic package.

greatly reduces the cost. However, inherent porosity of MIM and PM stainless steel cannot be avoided, and the porosity has a great influence on defect formation of the welding joints such as cracks and hole formation, resulting in degradation of stability and additional postwelding-shift (PWS). In this work, by using the MIM method, laser welding defect mechanisms, defect-free welding joints, PWS, and reliability are studied.

2 Experimental Setup

The laser welding system used in this study, as shown in Fig. 2(a), consists of three subsystems: an alignment system, a Nd:YAG laser system, and a process controller. The main laser beam from the laser cavity is separated into three beams by three partial mirrors with different reflections to achieve beam balance of less than 3%. Three laser beams are delivered by 600-μm step-index optical fibers and subsequently focused on the workpiece with the focal spot size of 400 μm in diameter. Each beam is precisely adjusted with the incident angle of 45 ± 1 deg and positioned 120 deg apart from each other. To reduce the metal oxidation during the laser welding process, nitrogen gas is used to shield the melting metal. The welding parameters, such as laser power (P), pulse duration (T), and pulse energy (E), affect the joint quality in the laser welding process. High laser power and pulse energy cause holes, cracks, and metal injection.[9] In this study, laser power and pulse duration are controlled and selected as 0.6 to 1.6 kW and 2 to 6 ms, respectively.

The cylindrical-type laser module based on a TO-type laser package and pigtail construction as shown in Fig. 2(b) is employed to investigate PWS. The laser module has a laser part and a pigtail fiber part assembled by laser welding. The laser part consists of a 1310-nm TO-type laser package with a built-in 1.5-mm ball lens and a laser housing made of MIM SS316L, which is used to replace the box-type body of bidirectional or triple-directional optoelectronic modules. The TO-type laser package is pressed

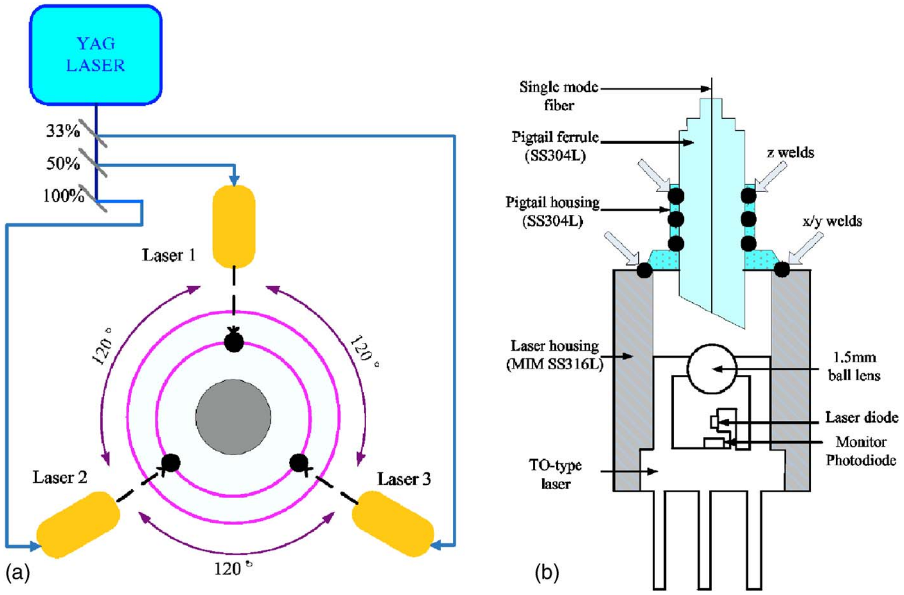

Fig. 2 (a) Schematic diagram of the laser welding system. (b) Configuration of the cylindrical-type laser module.

into the laser metal housing and then bonded with thermal epoxy. The pigtail fiber part consists of a SS304L pigtail ferrule with a single-mode fiber and a pigtail housing made of SS304L fabricated by conventional machining. The pigtail ferrule and the pigtail housing are jointed by laser welding. To provide good contact of two welded surfaces, fabricating accuracies of metal parts including perpendicularity, parallelism, flatness, and roughness are less than ±50 μm.

3 Results and Discussions

The MIM process includes powder mixing, molding, debinding, sintering, and surface treatment. Figure 3 shows the microstructures of MIM SS316L and PM SS316L with 97 and 85% of full density, respectively. The pores with diameters of 2 to 5 μm in MIM SS316L are isolated by a matrix, but those in PM SS316L are continuous and cross-linked. The pores have a detrimental effect on the laser welding joints. Therefore, the defect mechanism of the welding joints, MIM SS316L and PM SS316L jointed with SS304L with full density, are investigated by metallurgical analysis of a cross section, as shown in Fig. 4. Most pores in the molten pool of MIM SS316L disappear, but holes arise when laser power is more than 1.2 kWs. Among welding parameters, the laser power dominates hole formation, and the dimension of the hole increases as the laser power increases. The possible cause of hole formation is that gas trapped in the pores of MIM SS316L absorbs heat from

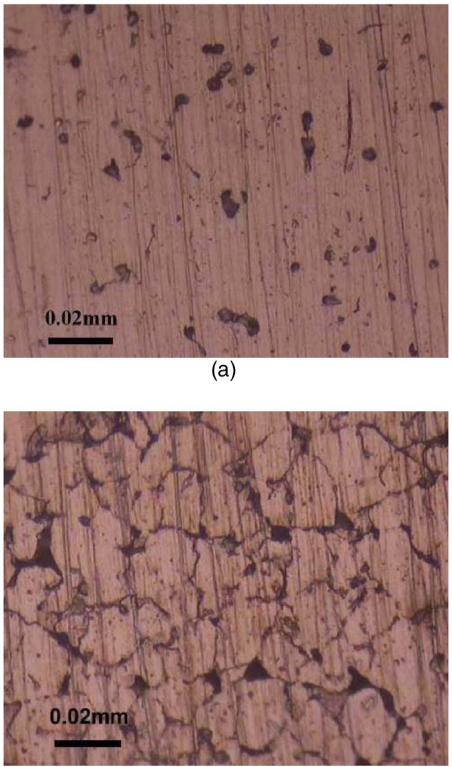

Fig. 3 The microstructure of MIM SS316L and PM SS316L with 97 and 85% of full density, respectively. (a) MIM SS316L and (b) PM SS316L.

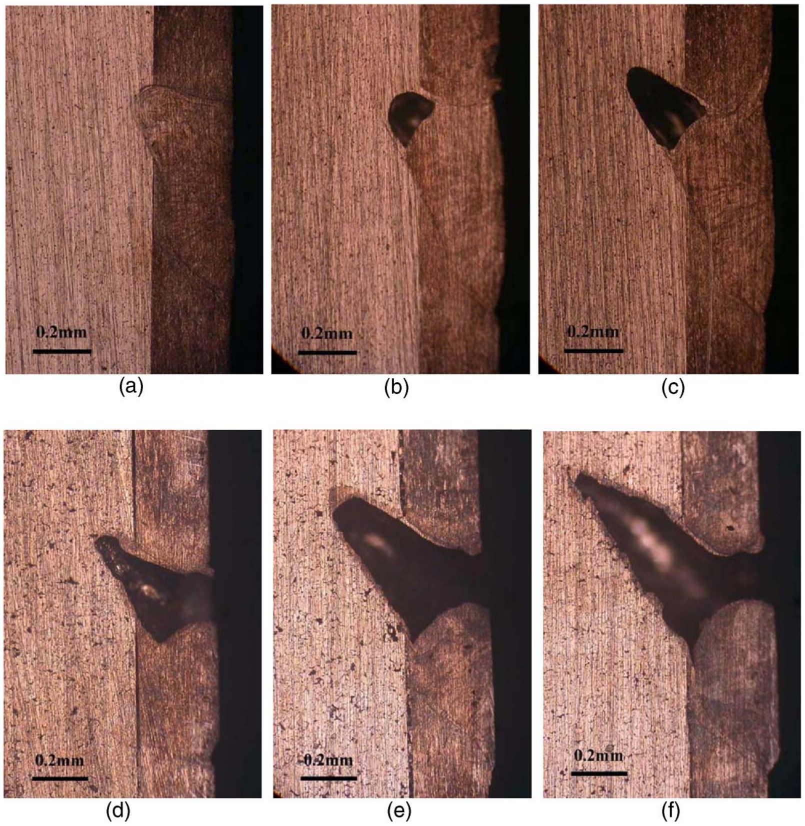

Fig. 4 The welding joints of MIM SS316L (left) and SS304L (right). (a) P: 1.0 kW and T: 3 ms. (b) P: 1.2 kWs and T: 3 ms. (c) P: 1.4 kWs and T: 3 ms. The welding joints of PM SS316L (left) and SS304L (right). (d) P: 1.0 kW and T: 3 ms. (e) P: 1.2 kW and T: 3 ms. (f) P: 1.4 kW and T: 3 ms.

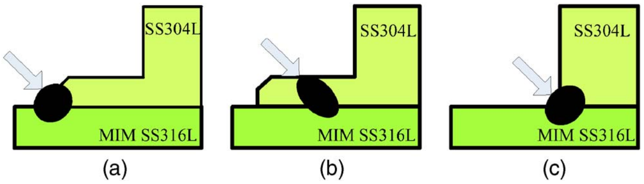

Fig. 5 Illustration of different welding geometries: (a) lap-fillet, (b) lap, and (c) fillet joints.

molten steel to expand, and subsequently nucleates and grows to form a hole in the welding pool. Because the laser beams have smooth Gaussian-like spatial extent in the cross section, the laser power has the maximum in the center of the optical axis with an incident angle of 45 deg. Thus, the holes always occupy the optical axis and are symmetric along the optical axis. As for the welding joints of PM SS316L and SS304L, as shown in Figs. 4(d)–4(f), defect-free welding joints cannot be achieved. Fully dense SS304L prevents the gas from expanding, and the pressure rises to push the molten steel out of the welding joints, resulting in weak and unstable welding joints.

The welding geometries, such as lap joints, fillet joints, and lap-fillet joints as shown in Fig. 5, greatly affect the joint strength and the stability of the welding spots.[7] To ensure long-term reliability of welding joints, the strengths of MIM SS316L jointed with SS304L are measured by a push test. Table 1 shows that the joint strength increases with laser power and energy. The lap joints need additional laser power and energy to penetrate the upper metal part. To accomplish stable lap joints of more than 15 kgs, the laser power of more than 1.2 kW is necessary. However, this results in hole formation and additional PWS.[9] For the fillet joints, less laser power and energy are required to achieve proper joint strength, but metal injection from upper metal parts reduces the welding strength and makes the joint unstable when the laser power is more than 1.2 kWs. In addition, the fillet joints are prone to welding cracks between two welding parts. The lap-fillet joint, extracting advantages from the lap joint and the fillet joint, is the optimal geometry for the welding joint. It provides a high joint strength to laser power ratio and diminishes metal injection and welding cracks. By optimizing welding parameters of laser power and pulse duration of 1.0 kw and 3 ms, respectively, the strength of the lap-fillet joint without any defect is more than 15 kg, which ensures long-term reliability.

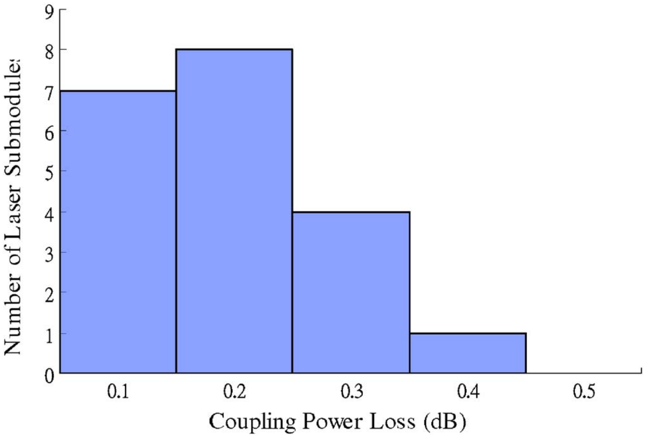

Fig. 6 Distribution of the coupling power loss due to the PWS.

PWS is attributed to the shrinkage during solidification of the molten metal pool between two welded parts. The scale of PWS is at the micron level so that direct measurement is very difficult.[10] The PWS in this study is estimated with the coupling power loss.[8] Before welding, the laser and single-mode fiber are precisely aligned to reach the maximum coupling power. After welding, the shrinkage of the welding pool gives rise to the transverse movement, which results in coupling power loss. The coupling power loss and the associated transverse movement can be used to determine PWS. The laser part and the pigtail fiber part are welded by using the lap-fillet joint with welding parameters of laser power and pulse duration of 1.0 kw and 3 ms, respectively. The SS304L ferrule and the pigtail housing are welded with the laser power and the pulse duration of 1.4 kws and 2.5 ms, respectively. Figure 6 shows the distribution of the coupling loss due to the PWS from 20

Table 1 The joint strengths (kg) of lap joint, fillet joint, and lap-fillet joint with various welding parameters. The deviation of joint strength is less than 10%. For the lap joint at 2 ms and 0.6 kw, no joint is formed. For the fillet joint at 2 ms and 1.2 kw, an unstable joint is caused by metal injection.

Pulse duration	Lap joint					Fillet joint					Lap-fillet joint				
Laser power	2 ms	3 ms	4 ms	5 ms	6 ms	2 ms	3 ms	4 ms	5 ms	6 ms	2 ms	3 ms	4 ms	5 ms	6 ms
0.6 kw	NJ	NJ	NJ	NJ	NJ	6.08	11.2	15.1	18.3	22.7	11.3	16.3	20.5	24.5	27.8
0.8 kw	NJ	NJ	NJ	NJ	2.1	10.5	15.9	20.3	24.8	27.7	13	21.3	25.5	29.5	32.5
1.0 kw	NJ	3.1	7.7	13.7	17.8	13.8	18.8	22.2	27.5	31	16.8	25.4	30.5	36	39.4
1.2 kw	0.9	12.3	18.2	23.7	29.7	MI	MI	MI	MI	MI	20.6	28.5	35.6	39.9	43.3
1.4 kw	5.9	15.0	23.0	30.3	37.4	MI	MI	MI	MI	MI	23.7	32.9	39.7	45.1	49.3
1.6 kw	10.8	21.2	28.6	38.9	47.9	MI	MI	MI	MI	MI	MI	MI	MI	MI	MI

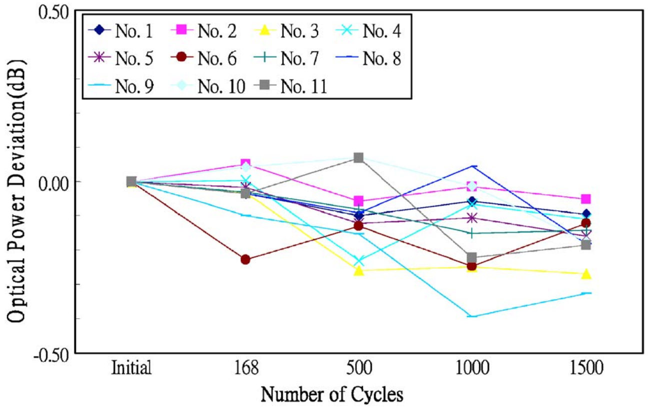

Fig. 7 Variation of optical coupling power with temperature cycling of 11 cylindrical-type laser modules.

pieces of the welded laser modules. The result indicates the coupling loss is less than 0.4 dB, which corresponds to the PWS of less than 1 μm. Although inherent pores of MIM SS3166L can be eliminated under optimal welding parameters which could lead to more PWS, PWS is still controlled under less than 1 μm.

To ensure long-term reliability, 11 cylindrical-type laser modules are subjected to temperature cycling tests according to GR-468-CORE[15] "Generic reliability assurance requirements for optoelectronic device used in telecommunications system." The temperature changes from −40 to 85 °C. The ramp rate is more than 10 °C/min, and the dwell time for −40 and 85 °C is 10 min. The pass/fail criterion of the power variation is 0.5-dB maximum change after 500 cycles. The variations of optical coupling power are measured as shown in Fig. 7. Even after 1500 cycles, the optical power variation is still less than 0.5 dB. This demonstrates that the optoelectronic packages fabricated with the MIM method are highly reliable.

4 Conclusions

In this study, cost-effective methods of fabricating metal parts by PM and MIM for optoelectronic packages are proposed. For the laser welding of PM SS316L, the rising gas pressure results in weak and unstable joints. For the laser welding of MIM SS316L, the laser power dominates defect formation. By using lap-fillet joints with a laser power of 1.0 kW and a pulse duration of 3 ms, stable and defect-free welding joints are attained, and the joint strengths are larger than 15 kgs. The coupling loss due to the PWS is less than 0.4 dB, corresponding to the PWS of less than 1 μm. After 1500 cycles of temperature cycling tests, the optical power variation is still less than 0.5 dB.

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References

1. H. Tanaka, N. Nakata, and K. Okada, "Cost-effective optical module for optical access system," *IEEE Photonics Technol. Lett.* **10**(3), 436–438 (1998).
2. A. Kawamura, S. Tabata, H. Sasaki, and T. Hatta, "Bidirectional module based on a diffractive optical element," Proc. ECOC(2004).
3. T. Hashimoto, T. Kurosaki, M. Yanagisawa, Y. Suzuki, Y. Akahori, Y. Inoue, Y. Tohmori, K. Kato, Y. Yamada, N. Ishihara, and K. Kato, "A 1.3/1.55-μm wavelength-division multiplexing optical module using a planar lightwave circuit for full duplex operation," *J. Lightwave Technol.* **18**(11), 1541–1547 (2000).
4. D. S. Alles, "Trends in laser packaging," in *Proc. 40th Electron. Comp. Technol. Conf.*, pp. 185–192 (1990).
5. M. R. Matthews, B. M. Macdonald, and K. R. Preston, "Optical components-the new challenge in packaging," *IEEE Trans. Compon., Hybrids, Manuf. Technol.* **13**(4), 798–806 (1990).
6. A. A. Hollander and K. J. Watkins, "The art and science of optoelectronic joining," *Photonics Spectra* pp. 110–114 (Oct. 1993).
7. B. Valk, R. Battig, and O. Anthamatren, "Laser welding for fiber pigtailing with long-term stability and submicron accuracy," *Opt. Eng.* **34**(9), 2675–2682 (1995).
8. M. K. Song, S. G. Kang, N. Hwang, H. T. Lee, S. S. Park, and K. E. Pyun, "Laser weldability analysis of high-speed optical transmission device packaging," *IEEE Trans. Compon., Packag. Manuf. Technol., Part A* **19**(4), 758–763 (1996).
9. W. H. Cheng, W. H. Wang, and J. C. Chen, "Defect formation mechanisms in laser welding techniques for semiconductor laser packaging," *IEEE Trans. Compon., Packag. Manuf. Technol., Part B* **20**(4), 396–402 (1997).
10. Y. C. Hsu, Y. C. Tsai, Y. L. Ho, M. T. Sheen, J. H. Kuang, and W. H. Cheng, "A novel alignment shift measurement and correction technique in laser-welded laser module packaging," *J. Lightwave Technol.* **23**(2), 486–494 (2005).
11. W. H. Cheng, M. T. Sheen, C. M. Cheng, and Y. T. Tseng, "An optimum approach for reduction of fiber alignment shift of fiber-solder-ferrule joints in laser module packaging," *J. Lightwave Technol.* **22**(2), 589–594 (2004).
12. Y. Lin, W. Liu, and F. G. Shi, "Laser welding induced alignment distortion in butterfly laser module packages: effect of welding sequence," *IEEE Trans. Adv. Packag.* **25**(1), 73–78 (2002).
13. R. M. German, *Powder Metallurgy Science*, Metal Powder Industries Federation, Princeton, NJ (1984).
14. R. M. German and A. Bose, *Injection Molding of Metals and Ceramics*, Metal Powder Industries Federation, Princeton, NJ (1997).
15. "Generic reliability assurance requirements for optoelectronic device used in telecommunications system," Bellcore, GR-468-CORE, December 1998.

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