Journal of Materials Processing Technology 210 (2010) 885–891

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Studies on the micro-laser spot welding of an NdFeB permanent magnet with a low carbon steel

Baohua Chang[a,*], Shaojun Bai[a], Dong Du[a], Hua Zhang[a], Y. Zhou[b]

[a] Department of Mechanical Engineering, Tsinghua University, Key Laboratory for Advanced Materials Processing Technology, Ministry of Education, Qing Hua Yuan 1, Haidian District, Beijing 100084, PR China
[b] Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, Ontario, N2L 3G1 Canada

ARTICLE INFO

Article history:
Received 3 June 2009
Received in revised form 20 January 2010
Accepted 30 January 2010

Keywords:
Micro-laser welding
NdFeB permanent magnet
Dissimilar materials
Process parameters
Fracture behavior

ABSTRACT

In search of high speed and miniaturization, the welding of NdFeB permanent magnet material is currently of increasing interest. Previous studies have shown that dissimilar material joining between magnet and steel sheets can be realized by laser irradiation, but it is still not clear how the welding parameters affect the weld quality. In this paper, the results are reported of experiments studying effects of laser pulse power, pulse duration, and defocusing distance on joint dimensions and mechanical behavior in laser spot welding of an NdFeB magnet (N48) with a low carbon steel (AISI 1006). Both conduction mode and keyhole mode welding were performed in the present study. The welding modes can be altered by changing peak power or defocusing distance, but not by changing pulse duration. Three fracture modes were found in shear tests, i.e., 'nugget pullout', 'through nugget' and 'magnet crush', while in peel tests, only 'nugget pullout' fracture mode was observed. The different fracture modes under different loading conditions were attributed to the mechanical locking effects present under shear testing but not under peel testing. For 'nugget pullout' mode fracture, the metallurgical quality of joints is the controlling factor of fracture forces; for 'nugget through' and 'magnet crush' mode fractures, the controlling factors are the size and strength of the nugget and base magnet. Certain nugget penetration should be achieved to avoid 'nugget pullout' fracture, while excessive growth of nugget should be limited to avoid 'magnet crush' fracture by appropriately adjusting process parameters.

1. Introduction

Since its birth in 1980s, the rare earth iron based permanent magnet material NdFeB has been developed very quickly and applied widely in many industrial fields, such as aeronautics, astronautics, automotive, appliance, computer and communications thanks to its excellent magnetic properties as indicated by Zhou and Dong (2004). To realize practical applications (e.g., to form necessary magnetic circuits) and avoid brittle fracture, the magnets are often bonded with other materials such as metals, ceramics and plastics. Currently, these bonds are implemented mainly by adhesive bonding or mechanical joining methods, which have lower productivity and poor joint performance (especially strength and durability) and cannot be easily applied on miniature structures. To meet the requirements of rapid production and structural miniaturization in advanced product designs, some novel joining technologies need to be developed for these magnets.

As one of the most important joining methods, welding has been used to join almost all engineering materials. However, the welding technology has not been used to join magnets in industry so far, and related studies are also very limited. Therefore, it is necessary to study the applicability of welding technology in joining small scale magnet components.

Among various welding processes, the laser welding process is considered as a good candidate to join tiny components (with thickness or diameter less than 0.5 mm) as stated by Zhou (2008), because of the lower heat input, small heat affected zone (HAZ), high precision and fast speed. In addition, no auxiliary materials (such as adhesives, bolts and solders) are required in laser welding. Chang et al. (2008) carried out a preliminary investigation on the micro-laser spot welding of NdFeB magnet with low carbon steel and indicated that the joining of these two dissimilar materials could be realized by laser irradiation. In addition, the joint formation mechanism, hardness distribution within the joint and the defects in HAZ were discussed. However, it is still not clear how the laser welding parameters can affect the weld quality and how the optimal welding quality can be obtained.

In this paper, the influence of process parameters (laser pulse power, pulse duration, and defocusing distance) on welding quality

---

[*] Corresponding author. Tel.: +86 10 6277 3860; fax: +86 10 6277 3862.
E-mail address: bhchang@tsinghua.edu.cn (B. Chang).

0924-0136/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2010.01.021

Table 1
Chemical compositions of the sintered NdFeB permanent magnet N48 (wt%).

Elements	Nd	Fe	B	Dy	Al	Si	C
Contents	31.10	64.27	1.02	2.54	0.45	0.17	0.070

Table 2
Chemical compositions of the low carbon steel AISI 1006 (wt%).

Elements	C	Mn	Si	P	S	N	Fe
Contents	0.06	0.28	0.003	0.009	0.015	0.005	Balance

in terms of nugget size and joint shear force are studied experimentally for micro-laser spot welding of NdFeB permanent magnet N48 and low carbon steel AISI 1006.

2. Experimental materials and methods

2.1. Materials

Sintered powder NdFeB permanent magnets N48 and cold rolled low carbon steel AISI 1006 were used in this study. The compositions of the materials are listed in Tables 1 and 2, respectively. The density of the magnet is 7.45 × 10^3 kg/m^3, and the microstructures of both the magnet and the steel are shown in Fig. 1. From Fig. 1a, it can be seen that in the magnet the main magnetic phase ($Nd_2Fe_{14}B$) is gray and distributed non-uniformly; Nd-rich phase is white and exists along grain boundaries or at intersections of grain boundaries of the main phase; the dark regions are voids. As for the microstructure of low carbon steel AISI 1006 shown in Fig. 1b, because the carbon content is low, it consists of mainly ferrite with average grain size of 30 μm and some dissociate cementite with average grain size less than 5 μm.

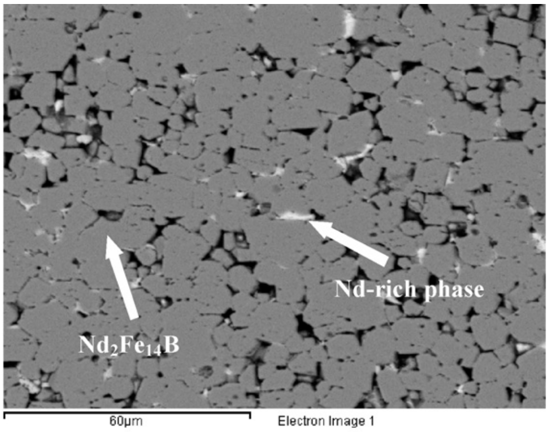
The magnets were cut into specimens with dimensions of 7.5 mm × 3.5 mm × 0.7 mm, and the steel sheets were cut into specimens with dimensions of 7.5 mm × 3.5 mm × 0.3 mm. Sodium hydroxide and nitric acid solutions were adopted in turn to remove grease and oxide layers from the specimen surface prior to laser welding. As indicated by Nunoko et al. (2007), the Nd element in the magnets was chemically active, so the experimental materials were welded immediately after cleaning.

2.2. Laser system and process parameters

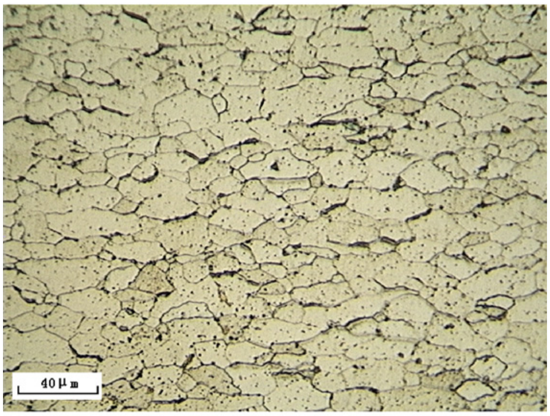
A GSI JK300HP type Nd:YAG pulsed laser welding system was used, which had a wavelength of 1064 nm, maximum mean power output of 300 W, and pulse duration range of 0.2–20 ms. Laser output was in the mode TEM_{00}, which was the fundamental transverse mode of the laser resonator and had a Gaussian distribution of energy intensity, as indicated by Norrish (2006).

The process parameters related to the pulsed laser are presented in Fig. 2. The energy of a single laser pulse, E_p, can be calculated by the area of the shadowed region. The peak power of laser pulse $P_p = E_p/t_p$, where t_p is the pulse duration. Each pulse can be determined by its t_p and P_p. The mean power of pulsed lasers $P_m = E_p/t_f$, where t_f is the inverse of pulse repetition f. The peak power density $P_d = P_p/D$, where D is the area of laser spot at the top surface of a specimen, and $D = \pi d^2/4$ with d denoting the laser spot diameter. The laser spot area is related to the position of laser focus indicated by defocusing distance z, as illustrated in Fig. 3. The defocusing distance refers to the distance between the focus and the top surface of the specimen being processed, and is generally a plus value when the focus is above the specimen top surface, zero when the focus is at the specimen top surface, and a minus value when the focus is below the specimen top surface.

In the micro-laser spot welding of magnet/steel specimens, each laser spot was formed by a single laser pulse. The laser energy input and its intensity can be determined by three process parameters, i.e., peak power P_p, pulse duration t_p and defocusing distance z. Therefore, effects of these three parameters on welding quality were mainly investigated in this study.



(a) Microstructure of NdFeB permanent magnet



(b) Microstructure of low carbon steel AISI 1006

Fig. 1. Microstructures of two base materials. (a) Microstructure of NdFeB permanent magnet. (b) Microstructure of low carbon steel AISI 1006.

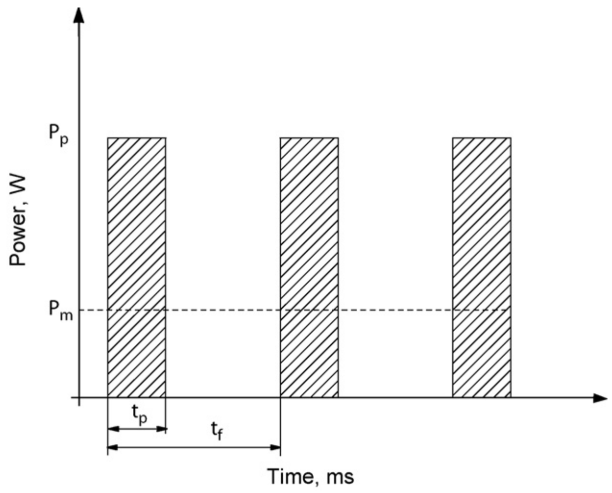


Fig. 2. Schematic of pulsed laser output.

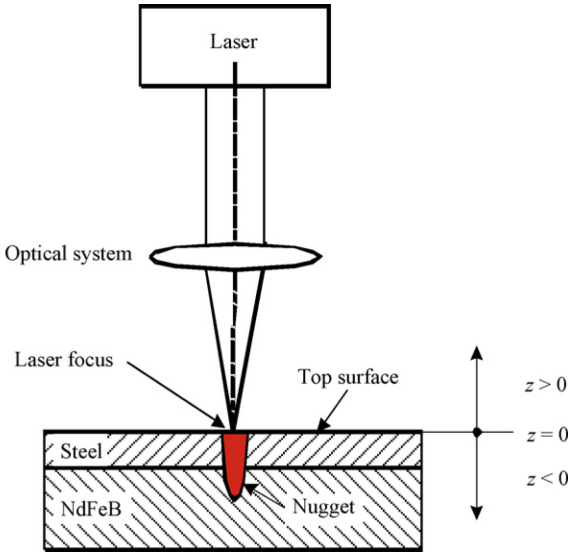


Fig. 3. Schematic setup of laser spot welding illustrating the defocusing distance and its sign.

2.3. Joint form and quality evaluation

As shown in Fig. 3, during the laser spot welding process, the overlapped samples were fixed in a specially designed clamp, with sheet steel on top of the NdFeB magnet. Chang et al. (2008) reported that the exposure of specimens to a laser irradiation would result in temperature increase, materials melting and solidifying and finally formation of a nugget to join the two specimens together. Argon with a high purity of 99.99% was used as shielding gas during welding.

Bransch et al. (1994) studied the effects of pulse shaping on Nd:YAG spot welds in austenitic stainless steel, in which the characteristic dimensions of a laser spot weld including diameter, penetration and melted area were mainly used to evaluated the weld quality. Liao and Yu (2007) used penetration depth, bead length and bead width to characterize the size of a welded spot when they studied the effects of laser beam energy and incident angle on the pulse laser welding of stainless steel thin sheet. Similarly, the welding quality in the present study was also evaluated in terms of dimensions of spot welds at first. After welding, the samples were mounted in epoxy resin, sectioned and polished to measure the weld dimensions. The characteristic dimensions of a laser spot weld in the present study included the spot diameter at the surface, D_s, penetration of nugget, P_n, and spot diameter at the interface between steel and magnet, D_i, as illustrated in Fig. 4.

Because the shear load is the main load applied on specimens in some applications (such as magnetic circuits in sound systems), the shear forces required to fracture the laser spot welds were measured with a SHIMPO FGN-20B digital force tester, and the fractured specimens were observed with scanning electron microscope (SEM) to study the fracture behavior of joints formed under various welding conditions. In addition, peel tests were carried out on the laser spot welds to compare the fracture behaviors under different loading conditions (shear versus peel).

3. Experimental results

3.1. Effects of peak power P_p

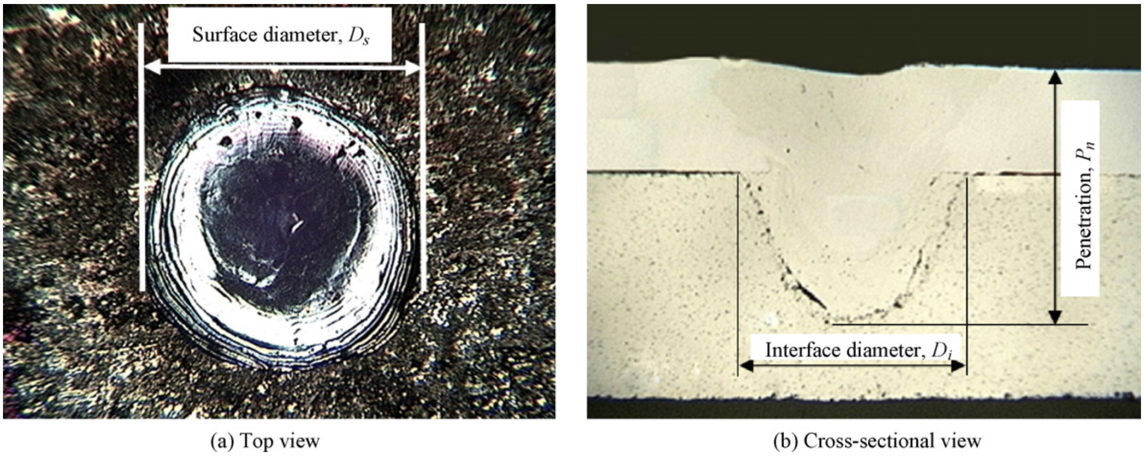
The overlapped steel/NdFeB specimens were laser spot welded under five levels of peak power, namely 500 W, 562.5 W, 625 W, 687.5 W and 812.5 W, respectively. Various peak powers were achieved by adjusting pulse energy, while the other process parameters were unchanged, i.e., pulse duration of 16 ms, and defocusing distance of 0 mm. Fig. 5 presents the characteristic dimensions and shear forces for various pulse peak powers.

As shown in Fig. 5a, all characteristic dimensions increased with increased peak power of laser pulses. Obviously, when the peak power is increased, the heat input to the specimen is increased and more material is melted, and the weld pool expands in both radial and depth directions. From Fig. 5b, it can be seen that the shear loads required to fracture the joints during shear testing also increased with the increase of laser pulse peak power.

3.2. Effects of pulse duration t_p

Five levels of pulse duration, 12 ms, 14 ms, 16 ms, 18 ms and 20 ms, were employed to laser spot weld the low carbon steel and NdFeB magnet components, with peak power and defocusing distance of the laser fixed at 625 W and 0 mm, respectively. The variations of characteristic dimensions and shear forces of spot welds with the pulse duration are plotted in Fig. 6.

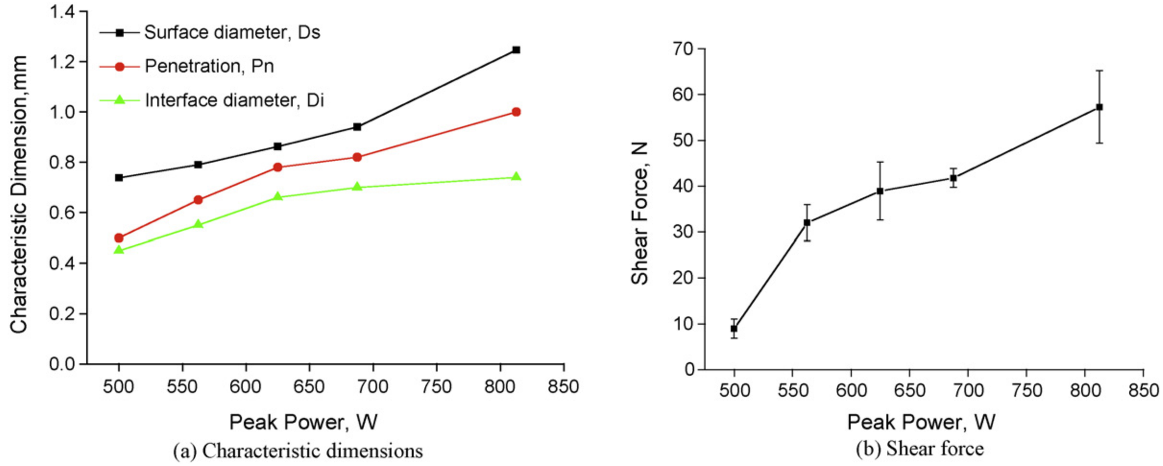
From Fig. 6a, it can be seen that both spot diameters at surface and steel/magnet interface increased for the increased pulse duration. As far as the penetration is concerned, increasing pulse duration from 12 ms to 14 ms could increase the penetration, while



(a) Top view

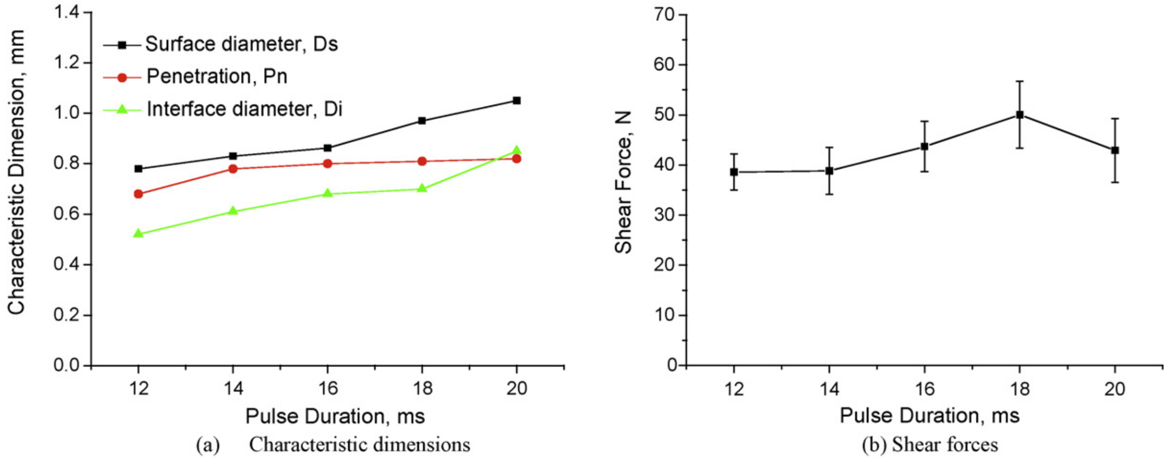
(b) Cross-sectional view

Fig. 4. Characteristic dimensions of a spot weld. (a) Top view. (b) Cross-sectional view.



(a) Characteristic dimensions (b) Shear force

Fig. 5. Effect of peak power of laser pulse on welding quality. (a) Characteristic dimensions. (b) Shear force.



(a) Characteristic dimensions (b) Shear forces

Fig. 6. Effect of pulse duration of laser on welding quality. (a) Characteristic dimensions. (b) Shear force.

further increasing from 14 ms to 20 ms had little influence. When the peak power of a laser pulse is given (625 W), changing the laser pulse duration appears to mainly affect the spot weld dimensions in the radial direction, and its influence on penetration is negligible.

As shown in Fig. 6b, increasing the pulse duration from 12 ms to 18 ms resulted in increasing shear forces of joints, while further increasing the pulse duration to 20 ms led to a decrease in shear forces. The shear force of these laser spot welds had a maximum value at the pulse duration of 18 ms.

3.3. *Effects of defocusing distance z*

Laser spot welds were made with defocusing distances ranging from 0 mm to +3.5 mm, while the peak power and pulse duration were fixed at 812.5 W and 16 ms, respectively. The variations of the characteristic dimensions and shear forces of laser spot welds with defocusing distances are shown in Fig. 7.

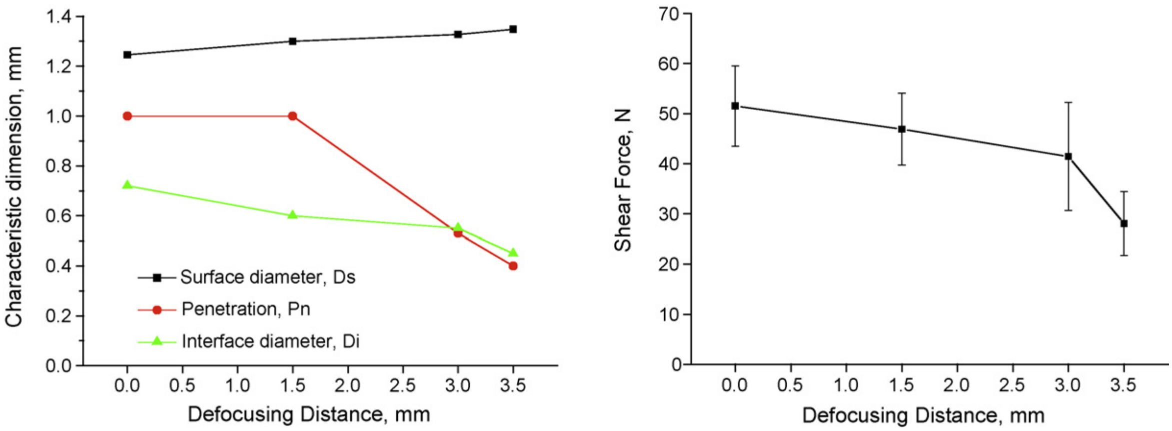
From Fig. 7a, it can be seen that the spot diameters at surface increased slightly for the increased defocusing distances, which results from the greater irradiation areas of the laser beam under larger defocusing distances. In contrast, both penetration (P_n) and spot diameter at the interface (D_i) decreased with the increasing of defocusing distances, which results from the reduced power density ascribed to the increased heating area. The shear forces decreased gradually with the increasing of defocusing distances, as shown in Fig. 7b.

4. Discussion

4.1. *Welding modes*

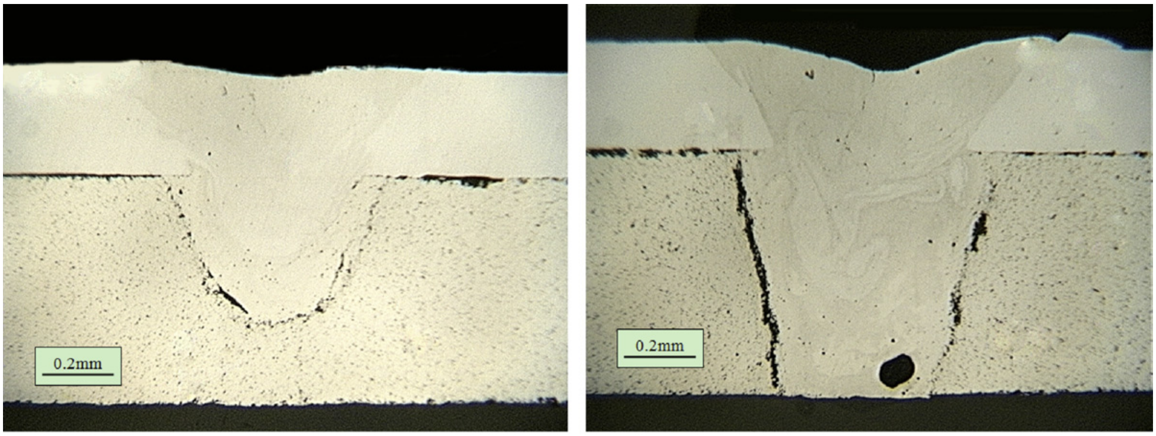
It is well known that two different modes are possible in laser welding, i.e., conduction mode and keyhole mode. The modes of laser welding are determined mainly by the power density of laser input. There exists a critical power density for certain materials, above which the laser welding is keyhole mode and below which it is conduction mode. The conduction limited laser welding typically produces welds with depth-to-width ratios less than 1, whereas the keyhole mode laser can produce depth-to-width ratios much greater than 1, as indicated by Norrish (2006).

Both welding modes were revealed in this study. In conduction mode welding, the cross-sections of nuggets were nearly semi-spherical or semi-elliptical, the magnets were not fully penetrated and the penetrations (P_n) were less than the surface diameters (D_s). For keyhole mode welding, due to the limitation of thickness ($0.3 + 0.7 = 1.0$ mm) of the materials combination in this study, the typical keyhole type nuggets (with depth-to-width ratio much greater than 1) were actually unavailable, and the specimens fully penetrated were considered having been welded with keyhole mode laser. Two typical



(a) Characteristic dimensions (b) Shear force

Fig. 7. Effect of defocusing distance on welding quality. (a) Characteristic dimensions. (b) Shear force.



(a) Conduction mode (b) Keyhole mode

Fig. 8. Nuggets formed under two different welding modes. (a) Conduction mode. (b) Keyhole mode.

nuggets formed under different welding modes are shown in Fig. 8.

When the peak power of laser pulse was 687.5 W, the magnet was partially penetrated ($P_n = 0.82$ mm), and when the peak power of laser pulse was increased to 812.5 W, the magnet became fully penetrated ($P_n = 1.0$ mm), as can be found in Fig. 5. This means the laser welding process is transferred from conduction mode to keyhole mode. The laser spot diameter is 0.35 mm when the laser is focused at the top surface of the specimen ($z = 0$ mm). Therefore, the critical power density for mode transition from conduction to keyhole is about $(7.15–8.44) \times 10^5$ W/cm^2. From Fig. 7, it can be found that the welding transfers from keyhole mode to conduction mode when the defocusing distance is increased; in contrast, the welding mode remains conduction and is not altered when the pulse duration is increased, as shown in Fig. 6.

4.2. Joint fracture modes

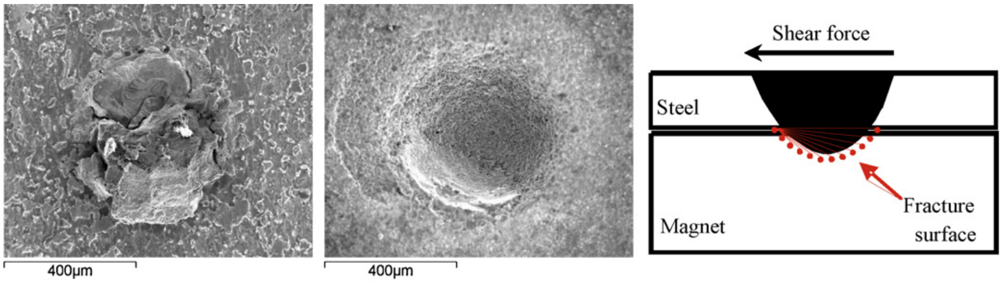
The fractured specimens from shear testing were examined using SEM and three different fracture modes were found, as shown in Fig. 9.

The first is 'nugget pullout' fracture mode shown in Fig. 9a, in which the nugget slide out of the base magnet and makes the joint failure. After testing, the nugget is still adjoined to the steel plate, while a pit is left in the magnet. This mode of fracture was generally found when penetration of the nugget were small (less than 0.5 mm), and the resulting shear loads were less than 30 N (see the first parameter setting in Fig. 5 and the last parameter setting in Fig. 7).

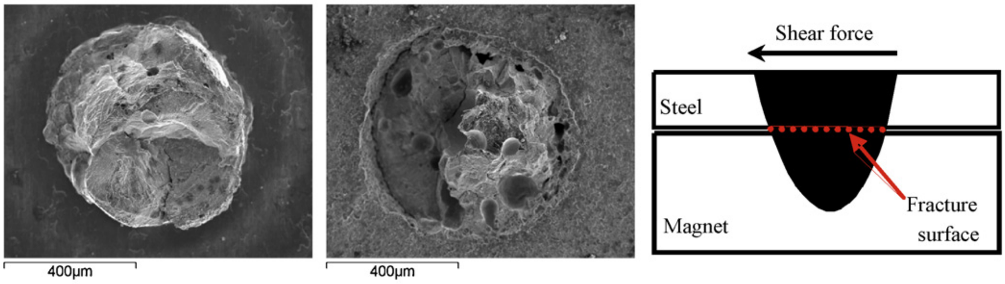
The second is 'through nugget' fracture mode, as shown in Fig. 9b, in which the nugget in a laser spot weld is broken into two parts along the interface between the steel and the magnet. The upper part of the fractured nugget remains adjoined to the steel plate, while the lower part is still bonded with the magnet. For this fracture mode, the nugget penetrations were greater than 0.5 mm, and the shear forces of joints increase with the interface diameters (D_i) of nuggets.

The third is 'magnet crush' type fracture, as shown in Fig. 9c, in which the magnet crushes into two or more pieces under pressure of the nugget while the nugget does not break itself. This mode of fracture was seen when the nuggets grow excessively in radial direction, and the base magnets were weakened too much (see the shear force decrease for the last parameter setting in Fig. 6). This phenomenon results from the severe reduction of load bearing area (i.e., unmelted area) of base magnet at the cross-section where the nugget is located.

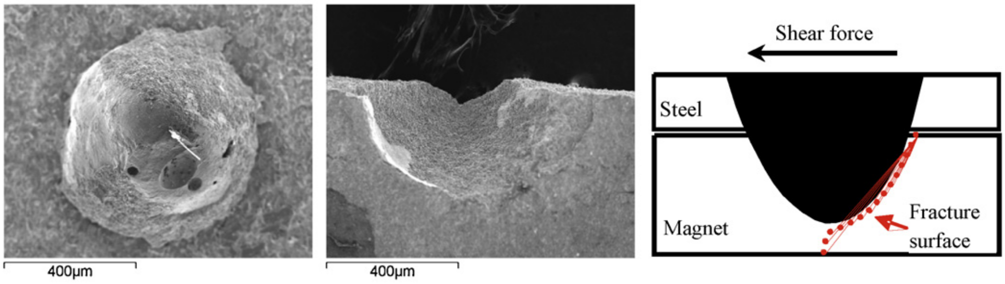
In contrast to three fracture modes in shear tests, only 'nugget pullout' mode (shown in Fig. 9a) was observed in peel tests. All samples broke along the profile of nuggets from the heat affected zone (HAZ) in magnet side, with fracture loads lower than 30 N. In terms of fracture forces, the shear loads are more favorable comparing to peel loads.



(a) nugget pulled out (left), pit in magnet (middle), and schematic (right) for the first fracture mode



(b) nugget adjoined to steel (left), nugget adjoined to magnet (middle), and schematic (right) for the second fracture mode



(c) unbroken nugget (left), crushed magnet (middle), and schematic (right) for the third fracture mode

Fig. 9. Three fracture modes in shear testing. (a) Nugget pulled out (left), pit in magnet (middle), and schematic (right) for the first fracture mode. (b) Nugget adjoined to steel (left), nugget adjoined to magnet (middle), and schematic (right) for the second fracture mode. (c) Unbroken nugget (left), crushed magnet (middle), and schematic (right) for the third fracture mode.

As can be seen that same fracture mode ('nugget pullout') occurred for spot welds under peel and shear loads when the nugget penetrations are less than 0.5 mm. In contrast, different fracture modes ('nugget pullout' for peel tests, 'nugget through' or magnet crush' for shear tests) happened under different loading conditions when the nugget penetrations are greater than 0.5 mm. In shear tests, the base magnet beneath the nugget can provide support to nugget and prevent it from sliding out when the nugget penetration reaches certain value (0.5 mm here), so the joints no longer fracture in 'nugget pullout' mode. Such interaction between the nugget and base magnet is referred to as mechanical locking effects in the study, which is negligible when the penetration depth is small (less than 0.5 mm). Differently, in peel tests there are no mechanical locking effects, so all joints fracture in 'nugget pullout' mode. Clearly, the mechanical locking effects are substantial causes for different fracture behaviors under different loading conditions.

4.3. Controlling factors of joint fracture forces

As indicated in Section 3.2, for all joints with small penetrations (less than 0.5 mm), despite the loading conditions, the cracks initiate and propagate in the heat affected zone (HAZ) of magnet. Sintered by powder metallurgy technology, the NdFeB permanent magnet contains large amounts of voids as shown in Fig. 1a, consequently, metallurgical defects such as cracks and porosity are likely to happen during laser spot welding. Such problems have been reported in the laser welding of other powder metallurgical materials. For instances, Mosca et al. (1983) examined the peculiarities of laser interaction with several types of powder metallurgical materials, and found notable cracks in the weld metal of medium carbon sintered steel and serious porosity in aluminium welds. Zhou et al. (2003) studied the porosity phenomenon in keyhole type laser welding of sintered cobalt powder and made attempts to solve the problem by adjusting process parameters and shielding gases in laser welding. In this study, the microstructure nearby the fusion line in the magnet side has been observed and is shown in Fig. 10. Micro-cracks are obvious in the heat affected zone (HAZ) of the magnet, which make the HAZ in magnet the weakest part of a joint. Obviously, the metallurgical quality has effects on the load bearing capability of spot welds, and improving the metallurgical quality of HAZ will increase the fracture loads of joints when the 'nugget pullout' fracture mode occurs.

The mechanical locking effects become significant when the nugget penetrations increase beyond 0.5 mm in shear testing, and the nugget no longer slides out of magnet. Under such conditions, the 'nugget through' or 'magnet crush' modes of fracture begin to occur, and the fracture mode to take depends on which one, nugget or base magnet, has higher load bearing capability. As we know the loading bearing capability is mainly determined by the strengths and sizes of the magnet and nugget. For given strengths of the nugget and base magnet, the sizes become determinative. When the nugget diameter is relatively small (Fig. 9b, right), the load bear-

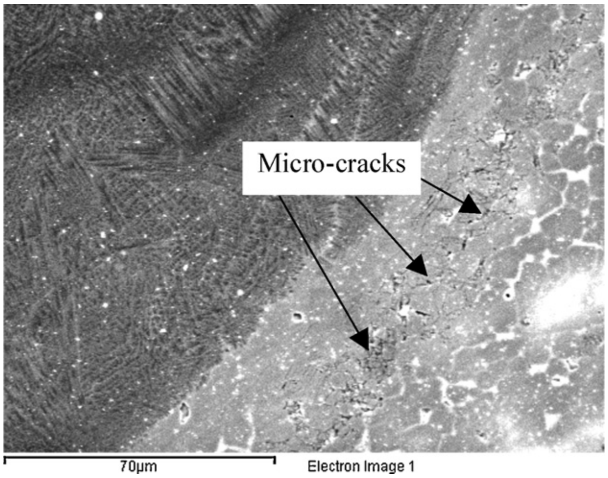


Fig. 10. Microstructure nearby the fusion line in magnet side.

ing capability of the base magnet is larger than the nugget, so the nugget will fracture under shear stress (in 'through nugget' mode), and the shear forces increase with the interface diameters (D_i) of nuggets. When the nugget diameter increase excessively (Fig. 9c, right), the remaining unmelted base magnet has lower load bearing capability than the nugget, then the magnet fractures under the pressure from the nugget (in 'magnet crush' mode).

In summary, for 'nugget pullout' mode fracture, the metallurgical quality of joints is the controlling factor of fracture forces; for 'nugget through' and 'magnet crush' mode fractures under shear loads, the controlling factors are the strength and size of the nugget and base magnet.

4.4. Selection of welding parameters

As discussed above, the joint quality in the laser spot welding of steel/magnet, in term of joint shear force, is related to both metallurgical quality and nugget dimensions. It is always necessary to appropriately select the process parameters to obtain desirable joint quality. From this study, it can be seen that to improve joint bearing capability under peer loads, the process parameters should be optimized to remove metallurgical defects (mainly micro-cracks) in the heat affect zone of magnets.

Under shear loads, to obtain high shear forces, certain nugget penetration should be achieved to produce mechanical locking effect and avoid 'nugget pullout' fracture. From Figs. 5–7, it can be found the penetration can be changed effectively by adjusting the peak power and the defocusing distance of laser pulse, while the penetration is not sensitive to pulse duration.

Moreover, larger interface diameters of nugget (D_i) will generally lead to higher shear forces in 'nugget through' mode fracture. But the excessive growth of nugget in radial direction will weaken the base magnet and lead to 'magnet crush' fracture with lower shear forces, and therefore should be controlled by limiting the pulse duration of laser.

5. Conclusions

Both conduction mode and keyhole mode welds may be formed in laser spot welding of NdFeB permanent magnets with low carbon steel. The critical power density for transition from conduction to keyhole mode is found to be about $(7.15–8.44) \times 10^5$ W/cm^2. The welding mode can be altered by adjusting the peak power and/or defocusing distance but not by changing the pulse duration.

Three types of fracture, namely, 'nugget pullout', 'through nugget' and 'magnet crush' have been revealed during shear tests of magnet/steel laser spot welds, while only 'nugget pullout' mode is observed in peel tests. The mechanical locking effects are the substantial causes for different fracture behaviors under different loading conditions.

For 'nugget pullout' mode fracture, the metallurgical quality of joints is the controlling factor of fracture forces; for 'nugget through' and 'magnet crush' mode fractures, the controlling factors are the size and strength of the nugget and base magnet.

The shear loads are more favorable to the joints comparing to peel loads in terms of fracture forces. To improve joint bearing capability under peer loads, the process parameters should be optimized to remove metallurgical defects (mainly micro-cracks) in the heat affect zone of magnets.

Certain nugget penetration should be achieved to produce mechanical locking effect and avoid 'nugget pullout' fracture at low shear forces by adjusting the peak power and the defocusing distance; the excessive growth of nugget in radial direction will lead to 'magnet crush' fracture at low shear forces, and therefore should be controlled by limiting the pulse duration of laser.

Acknowledgements

This work has been financially supported by the National Natural Science Foundation of China (www.nsfc.gov.cn, 50628506 and 50705049).

References

Bransch, H.N., Weckman, D.C., Kerr, H.W., 1994. Effects of pulse shaping on Nd:YAG spot welds in austenitic stainless steel. Weld. J. 73, 141–151.

Chang, B.H., Bai, S.J., Li, X.G., Ding, Y.Q., Zhang, H., Du, D., Zhou, Y., 2008. Laser spot welding of SPCC steel to NdFeB magnets. J. Tsinghua Univ. Sci. Technol. 48, 1728–1731.

Liao, Y.C., Yu, M.H., 2007. Effects of laser beam energy and incident angle on the pulse laser welding of stainless steel thin sheet. J. Mater. Process. Technol. 190, 102–108.

Mosca, E., Marchetti, A., Lampugnani, U., 1983. Laser welding of PM materials. Powder Metall. Int. 15, 115–118.

Norrish, J., 2006. Advanced Welding Processes. Woodhead Publishing Limited, Cambridge, England, pp. 144–148.

Nunoko, Y., Ohtsuka, T., Sakamoto, T., 2007. Passivation oxide film on Nd–Fe–B permanent magnets in borate buffer solution by ellipsometry. Corros. Sci. 49, 4005–4014.

Zhou, J.X., Tang, X.H., Zhou, Y., He, Y.Y., Zhu, G.F., 2003. Investigation of porosity defect phenomenon during laser welding of powder metal material. Laser Technol. 27, 503–505.

Zhou, S.Z., Dong, Q.F., 2004. Super Permanent Magnet: Rare Earth Iron Series Permanent Magnet, second ed. Metallurgical Industry Press, Beijing, pp. 1–5.

Zhou, Y., 2008. Microjoining and Nanojoining. Woodhead Publishing Limited, Cambridge, England, pp. xix–xxiv.