Nd-YAG LASER MICRO WELDING OF STAINLESS WIRE

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ABSTRACT

Applicability of laser micro welding process to the fabrication of medical devices was investigated. Austenitic stainless steel wire (SUS304) was spot melted and crosswise welded, which is one of the most possible welding process for the fabrication of medical devices, by using a Nd-YAG laser. Effects of welding parameters on the microstructure, tensile strength and corrosion resistance were discussed.

In the spot melting, melted metal width decreased with decreasing the input energy and pulse duration. Controlling the laser wave to reduce laser noise which occurred in the early stage of laser irradiation made reasonable welding condition wider in the welding condition of small pulse duration such as 2ms. The microstructure of the melted metal was a cellular dendrite structure and the cell size of the weld metal was about 0.5~3.5 μm. Tensile strength increased with the decrease of the melted metal width and reached to a maximum about 660MPa, which is comparable with that for the tempered base metal. Even by immersion test at 318K for 3600ks in quasi biological environment (0.9% NaCl), microstructure of the melted metal and tensile strength hardly changed from those for as melted material.

In the crosswise welding, joints morphologies were classified into 3 types by the melting state of lower wire. Fracture load increased with input energy and melted area of lower wire, and reached to a maximum about 80N. However, when input energy was further increased and lower wire was fully melted, fracture load decreased due to the burn out of weld metal.

KEYWORDS

micro laser welding, Nd:YAG laser, stainless steel, corrosion resistance, pulse wave shape

1. Introdution

Stainless steel is the first biomaterial which was used for the fixation of fracture bone in the 1920th and has come to be widely used as an artificial material[1]. At the present period, stainless steel is widely used also for medical devices, such as artificial joint, stent, guide wire, operation instrument etc, owing to mechanical properties, workability, low cost and corrosion resistance.

Recent upgrade of medical standards and development of technology made the demands against medical devices higher[2]. For instance, fabrication of much finer stent and coil anchor, which are implanted into blood vessel, were required to be applied for finer or more complicated parts of human body.

Actually, these medical devices are fabricated by plastic forming or laser cutting of stainless wires or tubes. However, by these methods, it takes high cost and is difficult to satisfy these demands, and establishment of micro laser welding technology is considered to be one of available methods for the fabrication of micro devices[3].

In this paper, applicability of laser micro welding process to the fabrication of medical devices was investigated. For a basic investigation, austenitic stainless steel wire (SUS304) was spot melted by using a Nd-YAG laser. Effects of welding parameters on the microstructure, tensile strength and corrosion resistance were discussed. Moreover, based on the results on spot melting, crosswise welding, which is one of the most possible welding process for the fabrication of medical devices, was performed to investigate the effects of welding parameters.

2. Experimental procedures

Austenitic stainless steel wire (SUS304) with a diameter of 0.25mm or 0.35mm was used in this study. All wires were welded by single pulsed laser irradiation using a Nd-YAG laser equipment (Lumonic JK701). Laser conditions were frequency : 20Hz, focal distance : 80mm, beam radius : 400 μm and atmosphere : Ar shield. Laser welding

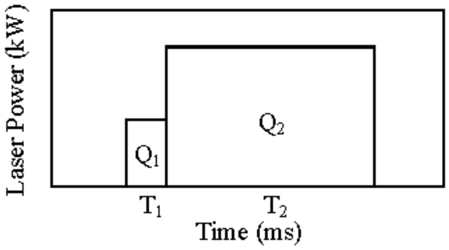


Fig. 1 Programmed laser power at each segment of time to minimize noise at laser irradiation

Table 1 Welding conditions to minimize noise for spot melting.
Definition of each parameter is shown in **Fig. 1**

Diameter (mm)	Pulse duration (ms)	T_1 (ms)	T_2 (ms)	Q_1 (J)	Q_2 (J)
0.35	1.0	0.3	0.7	0.15	0.21~1.05
	2.0	1.0	1.0	0.1	0.5~1.2
	10.0	2.0	8.0	0.2	1.8~4.8

parameters were input energy : 0.5~7.0J and pulse duration : 1~10ms for spot melting, and input energy : 3.0~10.0J and pulse duration : 10ms for crosswise welding. In the spot melting, controlling the laser wave to reduce this laser noise which occurred in the early stage of laser irradiation was performed. The methods of wave control were that input energy at the first pulse duration T_1 (ms) was Q_1 (J) and input energy at the rest pulse duration T_2 (ms) was Q_2 (J), as shown in Fig. 1 and Table 1. The measurement of laser wave was used by digital recorder (yokokawa 70180-1M/M2/C8).

Microstructural observation of weld metal and heat affected zone (HAZ) were performed by using optical microscope (OM) and scanning electron microscope (SEM). Tensile test was conducted at a cross-head speed of 3.3×10^{-3}mm/s. The specimen with a gage length of 100mm and a grab length of 150mm were applied to tensile test.

Immersion test was conducted at 318K for 1800ks and 3600ks in 0.9% NaCl quasi biological environment. Microstructure of the melted metal and tensile strength after immersion test were compared with those of weld joints before.

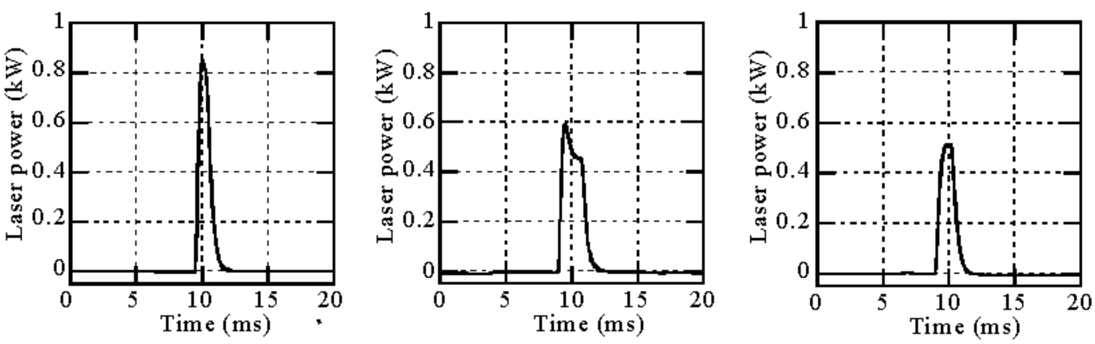
3. Results and discussion

3.1 Spot melting

3.1.1 Measurement and control of laser wave shape

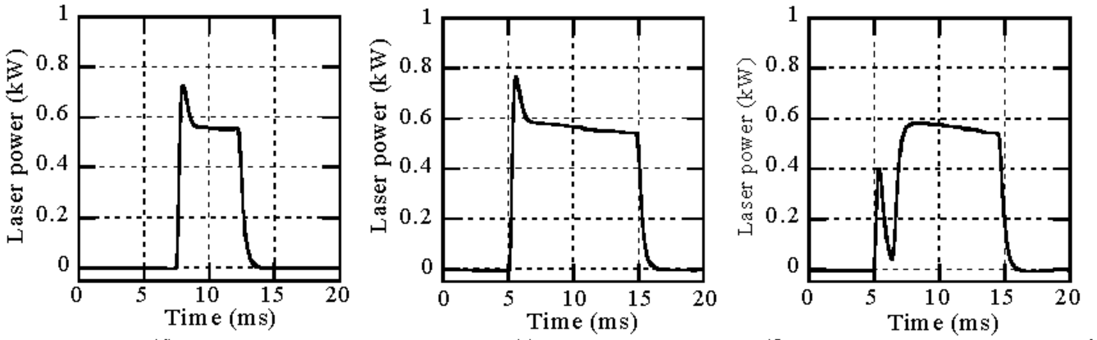
Figure 2 shows the wave shape of laser beam irradiated by various conditions. As shown in Fig. 2, in any conditions, laser noise, that is higher laser power than programmed one, appeared in the early stage of laser irradiation, and actually irradiated wave shape was not rectangle. Duration of laser noise was about 1ms in any conditions, and after that laser wave kept the stable state. Effect of laser noise was considered to become smaller with increasing the input energy and pulse duration, because ratio of laser power at noise against that at stable state was reduced.

In order to reduce the laser noise, controlling the laser wave was performed. In a pulse duration of 1ms, peak position was sifted slightly to the middle stage of laser irradiation. In a pulse duration of 2ms, laser noise was reduced and wave shape became almost rectangle, as shown in Fig. 2 (c). However, wave shape was likely to be sharpened with increasing the input energy. In a pulse duration of 10ms, a stable rectangle wave shape was not obtained, as shown in Fig. 2 (f). However, peak power of laser noise was less than that of stable state with increasing the input energy, and effect of laser noise was considered to be reduced.



(a) 1ms 0.9J (b) 2ms 1.0J (c) 2ms 0.1J+0.6J wave control

Fig. 2 Wave shape of laser beam irradiated by various pulse duration and input energy



(d) 5ms 3.0J (e) 10ms 6.0J (f) 10ms 0.2J+4.8J wave control

Fig. 2 Continued

3.1.2 Morphology and microstructure of spot melted metal

From the morphological observation of melted region, sound welding free from welding imperfection like crack and porosity was achieved. However, when pulse duration was small such as 1ms, welding imperfection like underfill was observed. Melted metal width decreased with decreasing the input energy and pulse duration. Figure 3 shows the laser condition range where reasonable welding can be achieved. In a pulse duration of 1ms, reasonable welding conditions were not decided, because morphology of the melted metal was unstable due to welding imperfection. Reasonable welding condition became narrower with decreasing the wire diameter and pulse duration. But for the small pulse duration such as 2ms, controlling the laser wave to reduce this laser noise made reasonable welding condition range wider.

Figure 4 shows the microstructure of spot melted metal. In entire laser conditions, the microstructure of the melted metal was a cellular dendrite structure that grew from fusion boundary to center of the melted metal, and δ ferrite was slightly observed around center of the melted metal. Cell size of melted metal was about 0.5~1.0 μm around fusion boundary and was about 3.0~3.5 μm around center of the melted metal, which became larger with increasing the input energy. By referring the relation between cell size and cooling rate, the cooling rate during laser welding was estimated about 2×10^6K/s around fusion boundary and about 5×10^3K/s around center of the melted metal[4].

3.1.3 Mechanical property

Figure 5 the shows the effect of Laser condition on tensile strength. In any welding conditions, tensile strength increased with decreasing the input energy and reached to a maximum about 660MPa. However, in a small pulse duration such as 1ms, different tendency was indicated as shown in Fig. 5. This was caused by the unstable morphology of the melted metal due to welding imperfection like underfill. Fracture occurred in the melted metal and fracture surface revealed cup-and-cone structure.

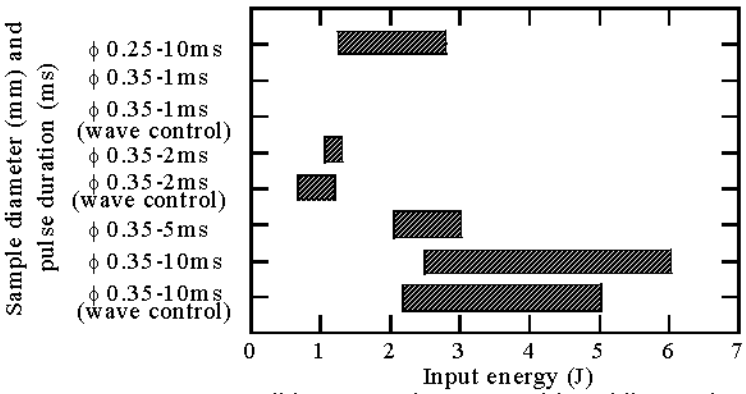
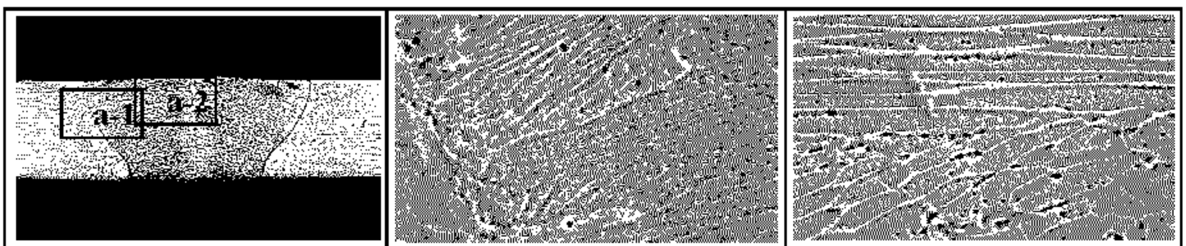


Fig. 3 Laser condition range where reasonable welding can be achieved



General view | (a-1) higher magnification | (a-2) higher magnification

Fig. 4 SE images of melted metal 10μm

Figure 6 shows the relation between tensile strength and melted metal width. As shown in Fig. 6, tensile strength increased with the decrease of melted metal width. It has been reported that tensile strength of weld joints including a soft interlayer depended on the relative thickness X (X was defined as the ratio of thickness of interlayer to specimen diameter) and increased with decreasing the relative thickness X. The tendency obtained in this study was similar to that. Therefore, it was found that the factor which affected tensile strength dominantly was not microstructure of melted metal but a melted metal width.

Compared with tensile strength of base metal, which was about 2300MPa with both diameters, that of spot melted material was smaller due to work hardening of base metal. Therefore, temper of base metal was performed to relieve work hardening. Tensile strength of the tempered base metal was about 600MPa. Consequently, tensile strength of spot melted material obtained in this study was considered to be comparable with that for the tempered base metal.

3.1.4 Corrosion property of melted material

As a result of cell size measurement, cell size was about 0.5~3.5 μm fine. It has been reported that corrosion property of weld metal that have the microstructure of cell size finer than about 3 μm was equated to that of base metal. In this study, cell size was 3.5 μm at the maximum[5]. Therefore, corrosion property of melted metal is considered to be comparable with that of base metal.

In order to investigate corrosion resistance of HAZ, electrolytic etch test using 10% oxalic acid was performed. After the etching, weld decay was not observed in the HAZ, and the HAZ exhibited step structure similar to that of the tempered base metal. It has been reported that microstructure of HAZ after the etch test was ditch structure when sensitization of HAZ occurred[6]. In this study, because ditch structure was not observed, it was considered that sensitization of HAZ obtained by laser welding did not occur. It is considered that this reason is that HAZ region is not hold in the temperature zone which sensitization occurs due to short laser irradiation and fast cooling rate.

Figure 7 and Fig. 8 shows the microstructural observation and tensile strength before and after immersion test which conducted at 318K for 1800ks and 3600ks in 0.9% NaCl quasi biological environment. As shown in Fig. 7, corrosion in the melted metal was not observed. Moreover, as shown in Fig. 8, tensile strength hardly changed from those for as melted material.

From these results, corrosion property of melted material is considered to be comparable with that of base metal.

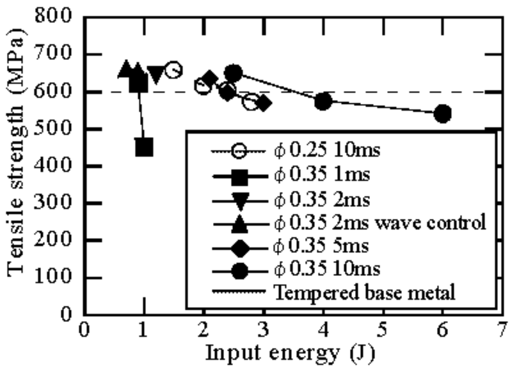


Fig. 5 Effect of welding condition on tensile strength

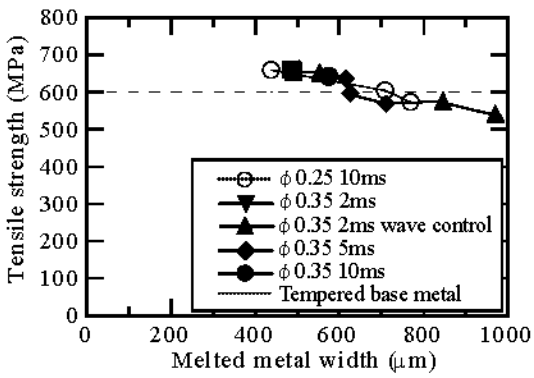


Fig. 6 Effect of melted metal width on tensile strength

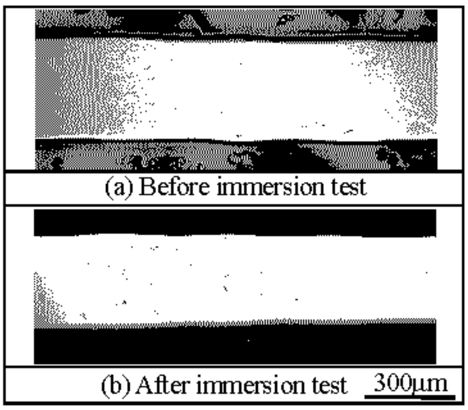


Fig. 7 Cross section of melted metal observed (a) before and, (b) after immersion test at 328K for 3600ks in quasi biological environment

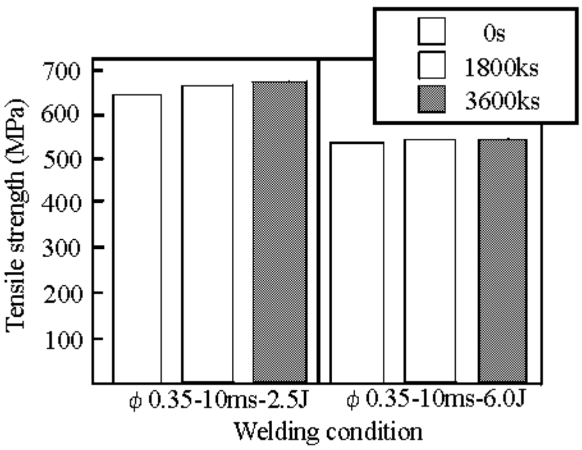


Fig. 8 Effect of testing time at 328k in a quasi biological environment on tensile strength

3.2 Crosswise welding

3.2.1 Morphology and microstructure of crosswise welded metal

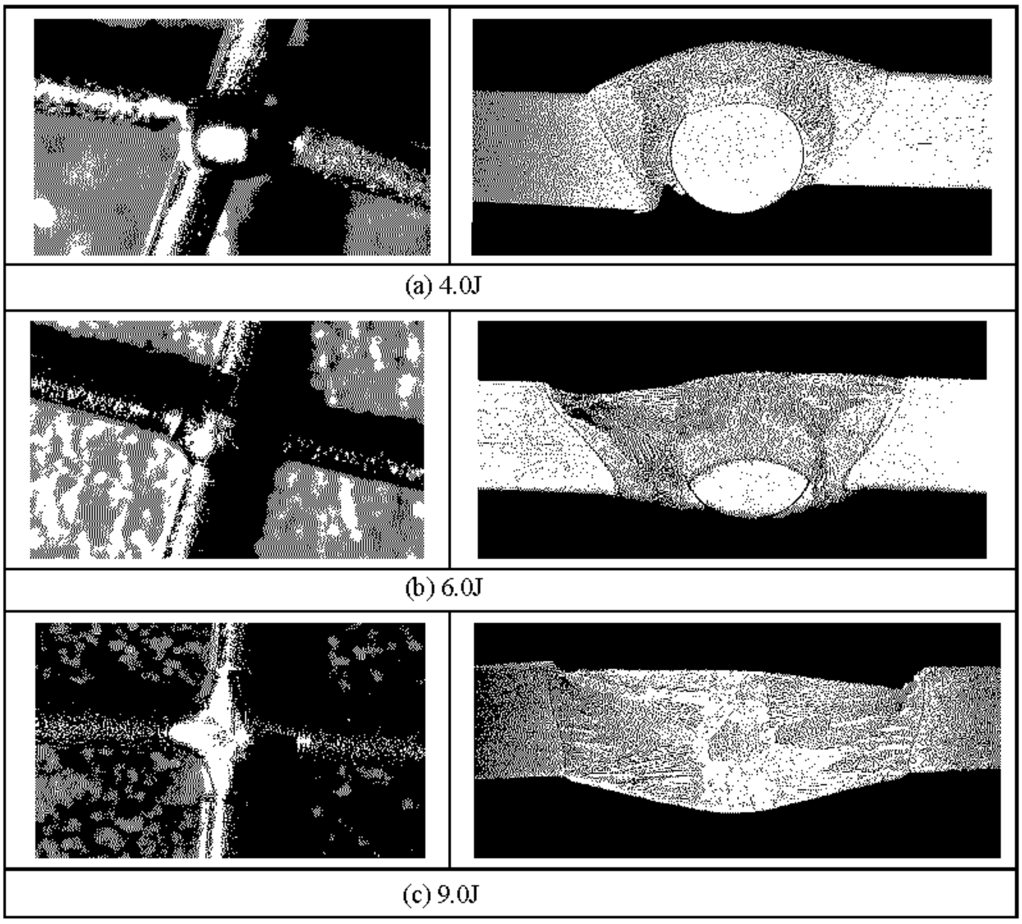
Figure 9 shows appearance and cross section of crosswise welded joints. Welding free from welding imperfection like crack and porosity was achieved. As shown in Fig.9, weld joints morphologies were classified into 3 types by the melting state of lower wire. Namely, lower wire is hardly melted, partially melted and fully melted, as shown in Fig. 9 (a), (b), (c) respectively. When input energy was less than 4.0J, lower wire was hardly melted. Melted area of lower wire increased with increasing input energy, and weldability was improved. However, when lower wire was fully melted, morphology of the weld metal was likely to be burn out, as shown in Fig. 9 (c).

The microstructure of the weld metal was a cellular dendrite structure similar to that of spot melted metal. Cell size was about 1.0μm around fusion boundary and about 5.0μm around center of the weld metal. By referring the relation between cell size and cooling rate, the cooling rate during laser welding was estimated about 4×10^5K/s around fusion boundary and about 1×10^3K/s around center of the weld metal. Although cell size of crosswise welded metal was a little larger than that of spot melted metal, it is considered that this slight differences does not affect the corrosion resistance.

3.2.2 Mechanical property

Figure 10 shows the effect of input energy on fracture load of joints. Fracture load increased with input energy and melted area of lower wire, and reached to a maximum about 80N in the morphology of weld metal as shown in Fig. 9 (b). However, when input energy was further increased and lower wire was fully melted, fracture load decreased. In entire welding conditions, fracture surface fractured ductilely with a cup-and-cone, although fracture path was different for joints each type of weld joints. When lower wire was hardly melted as shown in Fig. 9 (a), crack initiated from the boundary between non-melted area and lower wire, and propagated in the center of weld metal. When lower wire was partially melted or fully melted as shown in Fig. 9 (b), (c), fracture occurred in the boundary between weld metal and HAZ or in the weld metal.

From these results about the crosswise welding, it was important to melt the lower wire, but simultaneously it was needed that the laser condition should be controlled not to burn out the weld metal.



(a) 4.0J

(b) 6.0J

(c) 9.0J

Fig. 9 Appearance and cross section of crosswise welded joints 300μm

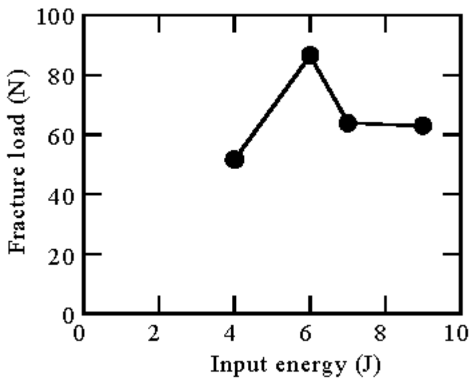


Fig. 10 Effect of input energy on fracture load of joints

4. Conclusions

Micro weldability of stainless steel wire by using YAG laser was investigated for application of laser micro welding to the fabrication of medical devices. The results are summarized as follows.

・Spot melting

1. Melted metal width decreased with decreasing the input energy and pulse duration. Controlling the laser wave to reduce laser noise which occurred in the early stage of laser irradiation made reasonable welding condition wider in the welding condition of small pulse duration such as 2ms.
2. The microstructure of spot melted metal exhibited a austenitic cellular dendrite microstructure with a cell size of about 0.5~3.5 μ m.
3. Tensile strength increased with the decrease of the melted metal width and reached to a maximum about 660MPa, which is comparable with that for the tempered base metal.
4. Corrosion resistance of melted metal and HAZ was comparable with that of base metal. Even by immersion test at 318K for 3600ks in quasi biological environment (0.9% NaCl), microstructure of the melted metal and tensile strength hardly changed from those for as melted material.

・Crosswise welding

1. Joints morphologies were classified into 3 types by the melting state of lower wire. Namely, lower wire is hardly melted, partially melted and fully melted. When lower wire was fully melted, burn out of weld metal was observed.
2. Fracture load increased with input energy and melted area of lower wire and reached to a maximum about 80N. However, when input energy was further increased and lower wire was fully melted, fracture load decreased due to the burn out of weld metal. For obtaining crosswise weld joints with high tensile strength, it was important to melt the lower wire, but simultaneously it was needed that the laser condition should be controlled not to burn out the weld metal.

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