

Laser welding of dissimilar materials with cast iron and carbon steel in differential gears

Daichi NISHIMOTO* Shota TSUDA* Takayuki TABUCHI* Shuichi SHIMADA** Takefumi SUZUKI*

Abstract

The electrification and downsizing of automobiles require welding of cast iron and carbon steel in power train components. However, delayed cracking is a problem in welding dissimilar materials including cast iron. As a countermeasure against delayed cracking, adding nickel (Ni) while welding is a technique used to reduce stress and ensure toughness, yet it is still difficult to eliminate the cracking. This paper investigated the results of welds composed of dissimilar materials, cast iron and carbon steel, and finds that stirring Ni is important. In addition, the following were observed in the welds: 1) The heat-affected part is harder than the molten part, creating a higher risk of cracking; 2) During welding, cooling rates sufficient to generate martensite are produced.

1. Introduction

In recent years, with the adoption of electric vehicles, space for mounting batteries must be ensured. Therefore, compact and lightweight power train components are required. Weight reduction is also required for gasoline-powered vehicles to achieve lower fuel consumption.

In differential gears, bolts have been used to join the case part (made of cast iron) that houses the differential mechanism and the final gears (made of carbon steel). As shown in Fig. 1, bolted joints are large to ensure the joint surface, and the weight also increases with the number of bolts. Laser welding has the potential to realize more compact and lightweight power train components, replacing this method of joining cast iron and carbon steel. However, the delayed cracking that occurs within a few days after welding is a problem in welding dissimilar materials including cast iron, making it difficult to apply laser welding to production.

In this paper, the following are investigated to reduce delayed cracking: 1) the state of the material microstructure changing depending on the laser irradiation conditions; and 2) the Ni distribution affecting the formation of the material microstructure.

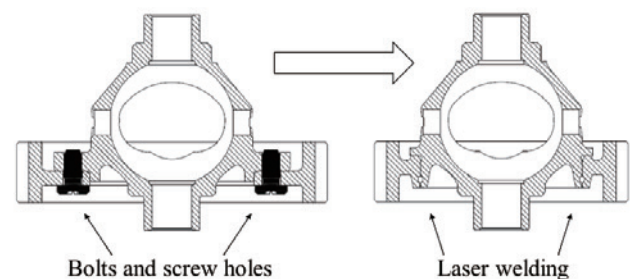


Fig. 1 Downsizing and weight reduction by laser welding

2. Causes and countermeasures for delayed cracking

Delayed cracking is considered to occur within 48 hours after welding the heat-affected or molten parts. The detailed mechanism causing delayed cracking has not yet been elucidated. As shown in Fig. 2, delayed cracking is considered to be caused by three factors: metal microstructure of the weld, diffusible hydrogen, and internal stress. Although the full picture of delayed cracking is still being studied, research has been conducted separately on each of the three factors. The following shows what have generally been observed.

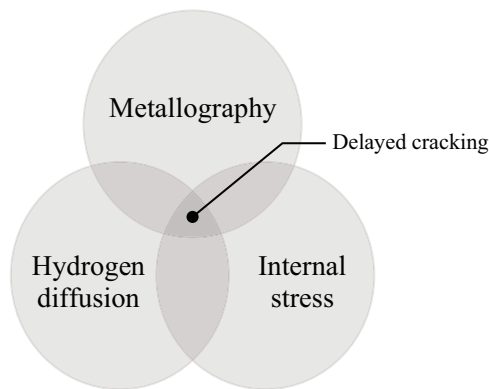


Fig. 2 Three elements of delayed cracking

2.1 Metal microstructure

From the viewpoint of metal microstructure, the formation of martensite in the heat-affected part exposed to rapid cooling is a cause of cracking. In welding, the temperature history applied to the material includes rapid heating and cooling. Therefore, hard microstructures such as martensite are easily formed. Martensite is formed by increasing the cooling rate in the temperature range from the melt temperature to around 500°C. Therefore, preheating and slow cooling processes are sometimes used to control the metal microstructure.

2.2 Diffusible hydrogen

Inside metal materials, there are hydrogen atoms that can move in the crystal lattice at room temperature. This hydrogen is called diffusible hydrogen. Diffusible hydrogen atoms tend to accumulate in highly stressed parts inside the material. Hydrogen embrittlement occurs when diffusible

hydrogen atoms accumulate in parts with a high internal stress produced by welding. The hydrogen embrittlement is known to be a cause of delayed cracking. Diffusible hydrogen can be either contained in the material before welding or entrained from the surroundings during welding. Reducing the amount of hydrogen remaining after welding is important as a countermeasure against delayed cracking.

2.3 Internal stress

In general, Ni is added in welding materials that includes cast iron. In production processes, a Ni alloy wire is fed during welding. The purpose of the Ni addition is to lower the residual internal stress. The thermal expansion coefficient is minimized when about 36% of Ni is added to iron (Fe)⁽¹⁾. This alloy is known as Invar. Its characteristic is used to reduce the amount of shrinkage of the molten part during cooling. In addition, Ni does not bond with carbon (C). Therefore, adding Ni is also effective from the viewpoint of ensuring toughness, as it prevents the hardening of the molten part in which C dissolves gathering from the surroundings.

This paper is the first step toward a full understanding of delayed cracking. We measured the Ni concentration distribution in the molten part and investigated the relationship between the occurrence of delayed cracking and the Ni concentration distribution as well as the laser irradiation conditions. From the viewpoint of metal microstructure, we also observed the microstructure of welds and measured the hardness distribution in order to investigate the relationship between the crack-generated and high-hardness sites. The temperature history was measured to confirm whether rapid cooling actually occurred to form the high-hardness microstructure.

3. Experimental methods and results

Figure 3 shows the overview of the laser welding experiment. The base metals are cast iron and carbon steel. Both were welded with the addition of 70%-Ni alloy wire having a diameter of 1.0 mm. The wire was fed into the molten bath from an angular direction of 45° viewed from the front side of the laser beam. For the shielding gas, N_2 was used. The laser used was a Yb:YAG infrared laser whose emitted beam had a focal diameter of 0.4 mm. The welding was conducted with six levels of conditions as shown in Table 1. Three levels—2,510 W, 2,650 W, and 2,710 W—were set for the laser power, and two levels, -2.5 mm and -3.0 mm, were set for the focal height measured from the weld surface. The welding state was photographed from above with a high-speed infrared camera. After welding, samples were cut in the direction shown in Fig. 4 to measure the Ni concentration distribution and hardness distribution.

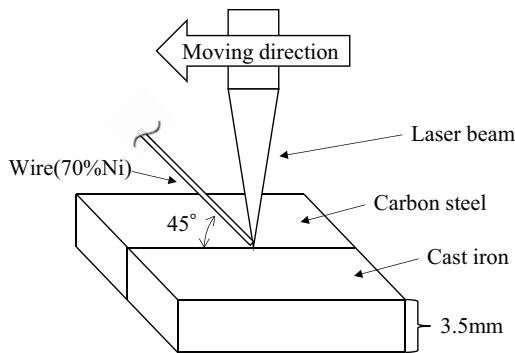


Fig. 3 Laser welding setup image

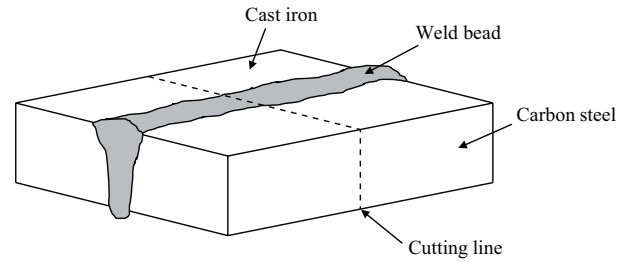


Fig. 4 Cutting

Table 1 Experimental settings

No.	Laser power (W)	Focus position (mm) (from surface)
1	2,510	-2.5
2	2,650	-2.5
3	2,710	-2.5
4	2,510	-3.0
5	2,650	-3.0
6	2,710	-3.0

3.1 Ni concentration distribution

3.1.1 Measurement method

An electron probe micro analyzer (EPMA) was used to measure the Ni concentration distribution. The EPMA is an elemental analysis instrument that lets electrons impinge on a sample to measure the characteristic X-rays emitted. The maximum acceleration voltage of the instrument used was 30 kV. The weld cross sections were measured and the color maps showing concentration distribution were created. The Ni alloy wire for welding was used as the reference for the concentration so that it could be visually compared based on the same level.

3.1.2 Results and discussion

Figure 5 shows the results of the color mapping of the Ni concentration distribution and the cracking occurrence level for each laser irradiation condition. The cracking occurrence level is evaluated and shown as a scale classified into three levels such as low, middle, and high. With a focal length of -2.5 mm, Ni stagnates at the top, whereas it reaches the bottom half part with a focal length of -3.0 mm. The Ni concentration distribution has a greater effect on cracking than the laser power, which can also vary the cracking rate.

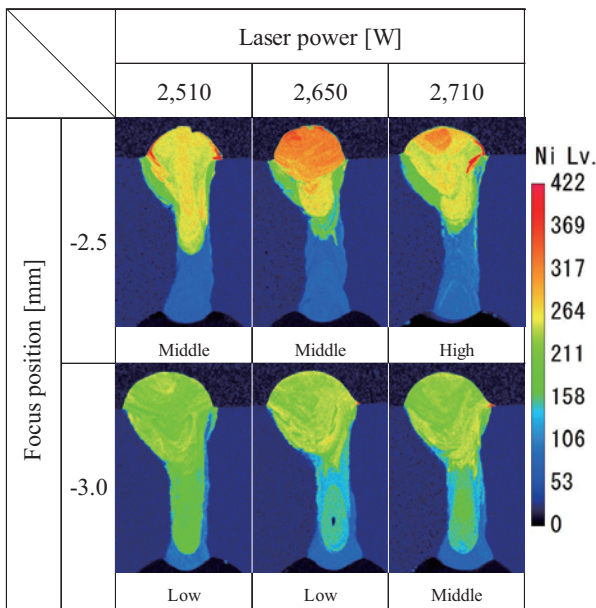


Fig. 5 Distribution of Ni and crack rate

3.2 Measurement of hardness distribution

3.2.1 Measurement method

A micro-Vickers hardness tester was used to measure the hardness distribution, with a load of 300 g and a pitch of 0.2 mm. The hardness distribution was mapped on an isometric photograph of the sample. The measurement area was 5 mm long (24 points) and 3.5 mm wide (17 points), including the molten and heat-affected parts on both sides of the sample.

3.2.2 Results and discussion

Figure 6 shows the results of the hardness distribution color mapping. The heat-affected part, especially on its cast iron side, shows a maximum hardness of over 600 HV. Microstructural observation in that part indicates the formation of martensite. The hardness of the molten part, on the other hand, is suppressed to 300 - 350 HV, indicating that the Ni addition is effective in ensuring the toughness of the molten part.

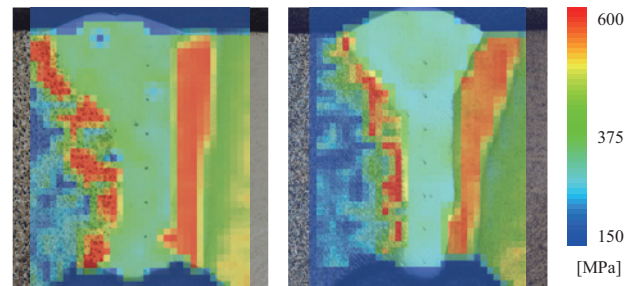


Fig. 6 Hardness distribution of welded area

3.3 Measurement of temperature history

3.3.1 Measurement method

The temperature history was measured using sample's image data taken by a high-speed infrared camera. It was capable of capturing images with a maximum pixel size of 640 × 512 and a frame rate of 1,000 fps. The wavelength sensitivity was set to 3,000 - 5,000 nm to exclude the influences of laser light and fumes. The captured image data were converted to temperature using the emissivity inherent to the materials. The elapsed time was calculated using positional information to create a temperature history graph.

3.3.2 Results and discussion

The process of creating the temperature history and the graph are shown in Fig. 7. The temperatures were calculated using the emissivity 0.35, which is the average of the emissivity values of 0.29 and 0.42 for cast iron and iron, respectively. On the surface of the molten part, rapid cooling at a rate of over $800^{\circ}\text{C}/\text{sec}$ is observed even after solidification. Cooling rates sufficient for the formation of martensite are supposed to occur even in the heat-affected part.

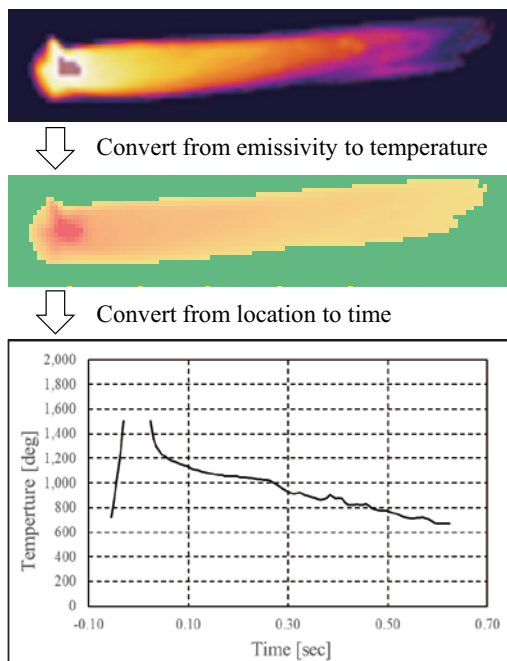


Fig. 7 Creating a temperature history graph

4. Summary

The microstructure was investigated as one of the three factors influencing delayed cracking occurring in welds composed of cast iron and carbon steel. The results obtained from this investigation are:

1. We established measurement methods for the Ni distribution, hardness distribution, and temperature history, which were visualized successfully.
2. The Ni distribution was found to have a significant effect on the cracking.

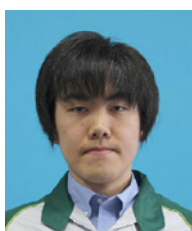
5. Challenges left for future

Using the measurement methods established in this study for the Ni distribution, hardness distribution, and temperature history, we will continue to investigate the mechanism causing delayed cracking from the viewpoint of metal materials. The investigation considering the other two factors, stress and hydrogen, will also be performed in order to elucidate the whole mechanism causing delayed cracking.

6. References

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- (2)Welding and Joining Technology, Japan Welding Society, ed., Sanpo Publications, 2015, pp. 200 - 202, 338 - 339.
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■ Authors ■



Daichi NISHIMOTO



Shota TSUDA



Takayuki TABUCHI



Shuichi SHIMADA



Takefumi SUZUKI