Laser Beam Welding of Nitride Steel Components

Hongping Gu\textsuperscript{a*}, Guobin Yin\textsuperscript{b} and Boris Shulkin\textsuperscript{a}

\textsuperscript{a}Stronach Centre for Innovation, Magna International, 375 Magna Dr., Aurora, ON, L4G 7L6, Canada
\textsuperscript{b}Unimotion Gear, Magna Powertrain, 245 Edward St., Aurora, ON, L4G 3M7, Canada

Abstract

Laser beam welding is a joining technique that has many advantages over conventional GMAW welding, such as low heat input, short cycle time as well as good cosmetic welds. Laser beam welding has been widely used for welding powertrain components in automotive industry. When welding nitride steel components, however, laser beam welding faces a great challenge. The difficulty lies in the fact that the nitride layer in the joint releases the nitrogen into the weld pool, resulting in a porous weld. This research presents an industrial ready solution to prevent the nitrogen from forming gas bubbles in the weld.

Keywords: Laser beam welding; nitride layer

1. Introduction

Laser beam welding is a joining process that is making revolutionary changes to many manufacturing processes and allowing for new design concept to be implemented. In many instances of powertrain component manufacturing, a gear component can be designed as a combination of several subcomponents. These subcomponents can then be welded together to form a functional part by taking advantages of laser beam welding. In this way, components containing multiple grades or multiple types of materials can be manufactured at relatively low production cost. As an example, a flexplate contains a ring gear welded to the outer rim of a thin disc of stamped steel. The main function of the flexplate in an automobile is to connect the transmission’s torque converter to the engine’s crankshaft. A flexplate is used instead of a solid, non-flexing disc because the torque converter’s outer metal shell tends to expand with heat under continuous operation and its flexing feature prevents it from cracking and failing prematurely. The ring gear is typically treated by carbonization to increase the hardness and wear-resistance of its teeth, while the stamped disc, usually large in diameter, is made of low carbon steel. In order to enhance the wear-resistance on the surface, nitridation of the discs is typically required by OEM manufacturers.

Under currently used manufacturing process, the flexplate is assembled mainly using GMAW welding technique. The weld is a fillet weld with weld metals added to the components. Following this step, it is typically required to weld a small weight onto the flexplate’s surface or to remove some material by drilling small holes on the ring gear in order to balance the rotating dynamics. Because of the additional mass, the rotating balance may be impacted with...
increased temperature. Therefore, laser beam welding process offers significant advantages for producing better products. Yet another benefit of laser beam welding is its high productivity compared to conventional GMAW. Multiple conventional welding stations can be replaced by a single laser welding station for achieving the same production rate.

In the case of welding flexplate, however, the nitride layer poses a great challenge to the laser beam welding process. In a typical configuration, the portion of the surface of the disc with the nitride layer is one of the joining surfaces in the butt joint. For GMAW, the fillet weld has a large open surface in the joining interface. The use of proper filler wire can overcome the difficulty caused by the nitride layer. However, laser beam welding is a deep penetration welding process and the nitride layer is deep inside the joint. In this case, the nitride layer is melted inside the weld pool during laser beam welding. As a result, the nitrogen is released into the weld pool and is retained within the weld pool. The nitrogen gas conglomerates to form bubbles during solidification.

Laser beam welding is a fast process that does not provide enough time for nitrogen to escape out of the weld pool under normal welding procedure. In several industrial research projects, attempts to weld by optimizing welding parameters and modifying beam characteristics did not achieve satisfying results. Until now, the only known successful laser welding for the nitrided flexplate is to remove the nitride layer in the joint prior laser beam welding. However, such an approach is not practical in volume production.

Filler wire was originally used to bridge the excessive gap in the joint in laser beam welding [1, 2]. It also makes it possible to weld certain aluminum alloys by supplying lost volatile alloying elements and modifying metallurgical property of the weld in order to prevent the weld metal from cracking [3, 4]. In this research work, the filler wire was used in laser beam welding to introduce certain alloying elements into the weld pool to capture the nitrogen, thus preventing nitrogen from forming gas bubbles in the weld. In this approach, therefore, the nitrogen forms metal nitride or nitrogen compound in the weld pool without leaving the metal matrix. This metal nitride stays chemically stable at elevated temperature. As a result, the laser weld maintains an acceptable quality with little or no porosity.

2. Experimental

In the experiment, the laser is a disk laser from Trumpf (model TruDisk 4002) with a maximum output power of 4 kW at a wavelength of 1030 nm. The beam quality at the rated power is 8 mm-mrad. The laser beam is delivered using an optical fiber of core diameter of 600 μm and is focused on the workpiece surface by a laser welding head (Trumpf D70). In this welding head, both collimating lens and focusing lens have a focal length of 200 mm. Hence, the beam spot size at focus is 0.6 mm in diameter.

The D70 welding head is mounted on the end effector of an ABB robot (model IRB4400). The robot is programmed to move the welding head to perform the welding. A simple but efficient wire feeding device was built based on a MIG welder. The wire feeder nozzle is mounted on the welding head so that their relative position is fixed. Figure 1 shows the setup for laser welding the flexplate with filler wire. During welding, the filler wire was fed directly into the front of the weld pool so that the filler wire material can mix efficiently with the melt metal in the joint.

Figure 1. Experimental setup for laser beam welding with filler wire
Metal cored wire was used in this research work. The benefits of utilizing metal cored wire come from its melting characteristics and its compositional formulation. Metal cored wire can be designed to alter weld metal composition. Addition of certain alloying elements in the wire can be easily achieved. Due to the powder filling in the core, the metal cored wire can be easily melted under single heat source from laser beam. The filler wire used in the experiment is the commercial-standard wire from Select Arc Inc, which is rich in titanium. Table 1 lists typical element composition in the wire.

Table 1. Material composition of the metal cored filler wire

| Typical deposit composition (wt%) |
|----------------------------------|
| C  | Mn  | P  | S  | Si | Cr  | Ti   |
| 0.03 | 0.60 | 0.01 | 0.01 | 0.69 | 11.90 | 1.00 |

The flexplate consists of a ring gear (SAE 1045/1050) and a stamped steel disc (SP231-440). The steel disc is gas nitrided with a tumble polish. The diffusion thickness of the nitrogen is 0.45 mm at a minimum and the compound layer thickness is ≥0.015 mm. The surface with nitride layer is one of the butting surfaces in the joint.

For microstructure and chemical element analysis, a JEOL 6380LV scanning electron microscope (SEM) and Oxford energy dispersive X-ray spectroscope (EDS) was used. The phase analysis to identify the existence of metal nitride was carried out using a PANalytical X’Pert PRO material research diffractometer (MRD). In the X-ray diffraction investigation, photography of the weld sample was performed using copper radiation (tension = 45 kV; current = 40 mA). The X-ray beam incident on the specimen was restricted by optics of mono-capillary 135*0.3 without filter. The diffraction beam was manipulated by the optics of a parallel plate collimator of 0.027 rad, without soller slit and Nickel filter.

3. Results and Discussion

Using laser beam welding under normal procedure without filler wire, a good cosmetic weld can be produced as shown in Figure 2(a). However, by examining the cross sections of the weld severe porosity is observed (Figure 2(b)). This porosity is caused by the nitrogen gas bubbles. During laser beam welding, the nitride layer is decomposed and releases its nitrogen into the weld pool under high temperature. Due to the fast solidification of the weld metal in laser beam welding, the nitrogen remains in the weld in the form of gas bubbles.

Once the filler wire is introduced in the weld pool, the welds are remarkably improved. No significant porosity can be seen inside the weld, as is shown in Figure 3. The welding was carried out by focusing the laser beam on the top surface of the joint. The laser beam power is 4 kW and the welding speed is 50 mm/s. The wire feeding rate is
approximately the same as the welding speed. Argon gas was used as the shielding gas to protect the weld metal from oxidation. By examining the weld under higher magnification, the main body of the weld was found not contain any gas bubbles, but at the root of the weld some small bubbles exists. The imperfection at the root indicates that the filler material may not reach to the bottom of the weld. However, such an imperfection does not affect the strength of the weld. In a destructive test of the finished flexplate that has 8-segment welds equally distributed along the joining interface, the part can hold more than 37,000 lb force before breaking the welds. As a reference, the rated specification for the push test of the part is 10,000 lb.

The remarkable improvement of the weld is achieved through the mechanism that the nitrogen in the weld pool forms metal nitride at elevated temperature without leaving the metal matrix. The metal cored wire that was used for welding is rich in titanium, as seen in table 1. Nitridation of titanium with nitrogen to form titanium nitride (TiN) takes place at very high temperature ($\geq1200$ °C) because of the very low enthalpy of TiN formation [5]. Titanium nitride has a very high melting point (2950 °C) and is chemically stable. Furthermore, titanium nitride hardly evaporates even at temperature close to its melting point [6]. During laser beam welding, the weld pool is at the temperature of the melting point of steel (1530 °C) or above. At such a high temperature, nitridation of titanium with nitrogen is readily taking place in the liquid state, thus capturing nitrogen in the metal matrix. As a result, gas porosity of nitrogen is prevented in the weld.

![Image of laser weld](image1)

Figure 3. Cross section of a laser weld which was produced by feeding a metal cored filler wire

![Image of SEM observation](image2)

Figure 4. SEM observation of the weld which shows dispersed black particles
SEM observation of the laser weld was carried out to examine the microstructure and the chemical composition of the weld. At sufficiently high magnification, many small black particles can be seen in the weld, as is shown in Figure 4. These small black particles were then analyzed using Oxford energy dispersive X-ray spectroscopy (EDS). The EDS analysis indicates that these black particles are Ti- and Cr-containing particles, that is, these particles contain significant amount of Ti and Cr elements, which are shown in the element spectra of Figure 5. The spectra also indicate the possibility of N contained in the black particles since nitrogen elements are difficult to detect.

Information about the chemical composition can be revealed by X-ray diffraction (XRD) analysis. Therefore, phase analysis of the laser weld with filler wire was carried out by using the PANalytical X’Pert PRO Material Research Diffractometer (MRD). In the XRD pattern, titanium nitride peaks, TiN(200) and TiN(111), can be identified, as is shown in Figure 6. This observation indicates that TiN phase is present in the weld. However, accurate measurement of the chemical composition is difficult since the cross section of the weld is quite small. In this study, the result of XRD phase analysis provides evidence of the formation of titanium nitride in the weld.

Figure 5. EDS analysis results of the black particles at two locations

Figure 6. Result of XRD phase identification analysis
Chromium is one of the main alloying elements of the filler wire that was used for the welding. Chromium starts to react with nitrogen to form simultaneously mono chromium nitride (CrN) and dichromium nitride (Cr$_2$N) at an elevated temperature (600 °C). But with rise in temperature (above 1100 °C), CrN decomposes and transforms into Cr$_2$N if there is enough reaction time. The dichromium nitride, on the other hand, is not stable with temperature. At a temperature above 1200 °C, Cr$_2$N starts dissociation. In this respect, chromium nitride is chemically unstable at the temperature of laser beam welding of steel. Nevertheless, it is possible that some chromium nitride remains in the weld after solidification. This portion of the metal nitride may have a contribution as well to the suppression of nitrogen gas bubbles in the weld.

4. Conclusion

Laser beam welding of nitride steel components, such as flexplate, is difficult due to the nitride layer in the joint. Under normal welding condition, melting of the nitride layer in the joint releases its nitrogen into the weld pool. Laser beam welding is a fast process. Because of the high speed of solidification of the weld metal, the nitrogen gas in the weld pool does not have enough time and the driving force to escape out of the weld pool. As a result, the finished weld contains significant amount of nitrogen gas bubbles.

In order to suppress the nitrogen to form gas bubbles in the weld, metal cored wire that is rich in titanium was used as the filler wire during laser beam welding. When the filler wire material is melted and mixed directly and efficiently with the molten metal in the joint, the titanium can readily form titanium nitride in the weld under such a high temperature. This TiN is chemically stable once it is formed, thus prevents the nitrogen from forming gas bubbles in the weld. With this approach, laser welds of good quality are successfully produced. XRD phase identification analysis of the laser welds provides evidence of the formation of titanium nitride in the improved welds. This welding technique would be a solution to the implementation of laser beam welding of nitride steel components such as flexplate in the car manufacturing.

Acknowledgements

The authors would like to thank Dr. Daolun Chen and Mr. Quang Li at the Department of Mechanical and Industrial Engineering of Ryerson University for the microstructure observation and chemical microanalysis using the SEM and EDS as well as the phase analysis using the X-ray diffraction (XRD).

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