Laser Beam Welding of 2205 Duplex Stainless Steel with Metal Powder Additions

H. C. WU, L. W. TSAY \(^1\) and C. CHEN

Department of Materials Science and Engineering, National Taiwan University, Taipei, 106 Taiwan.
E-mail: gchen@ccms.ntu.edu.tw
\(^1\) Institute of Materials Engineering, National Taiwan Ocean University, Keelung, 202 Taiwan.

(Received on June 1, 2004; accepted in final form on August 3, 2004)

Laser beam welding with the aid of metal powder additions to the weld pool was carried out to modify the ferrite/austenite (\(\alpha/\gamma\)) ratio of the weld metal of 2205 duplex stainless steel (DSS). The \(\alpha\) content in the weld metal of DSS welds could be controlled by the proper flow rate of nickel powder through a coaxial nozzle. This process had the advantage of using only a small amount of filler metal, i.e., a few grams per minute of nickel powder, in the welding process. Impact and notched tensile tests were utilized to evaluate mechanical properties of laser welds. The notched tensile test was also carried out in hydrogen under a slow displacement rate. The susceptibility to hydrogen embrittlement (HE) was estimated from the loss in notched tensile strength and correlated with the microstructure of a given laser weld. On the whole, the susceptibility to HE decreased with increasing the \(\gamma\) content of DSS welds. Autogeneous laser welds containing the highest \(\alpha\) content of all welds tested were most susceptible to HE. The base material with banded \(\alpha/\gamma\) structures was susceptible to HE and exhibited severe secondary cracks mainly along \(\alpha/\gamma\) phase boundaries. Although laser welds produced at a flow rate of 3 g/min nickel powder had similar \(\alpha\) content to the base material, they were more resistant to HE owing to randomly distributed \(\alpha\) and \(\gamma\) phases in the weld metal. The impact energy of laser welds at low temperatures (\(-75 \text{ to } -100\,\text{°C}\)) along with the hardness test could also be used to check if the proper amount of nickel powder was added in laser welding of DSSs.

KEY WORDS: laser beam welding; 2205 duplex stainless steel; notched tensile strength; hydrogen embrittlement.

1. Introduction

Duplex stainless steels (DSSs) are a family of two-phase alloys, consisting of austenite (\(\gamma\)) and ferrite (\(\alpha\)) with various proportions. The chemical composition of DSS is higher in chromium but lower in nickel than the austenitic stainless steels such as 304 and 316. The DSS combines the superior strength and stress-corrosion cracking resistance of the ferritic stainless steel, with good ductility and toughness of the austenitic stainless steel.\(^{1,2}\) DSSs such as 2205 and 2304, containing about 50% of each phase, are widely used as structural materials for piping, heat exchangers, pressure vessels etc.\(^{1,2}\) The optimum combination of mechanical and corrosion properties of such steels is accomplished when the \(\alpha/\gamma\) ratio is close to 1 through the careful control of compositions and thermo-mechanical treatments.\(^{3,4}\)

Generally, the weldability of the DSS is better than that of the austenitic stainless steel and worse than that of the ferritic stainless steel.\(^{5}\) In welding of DSSs, the appropriate phase balance of the weld metal is obtained by the addition of filler metal, which has a Ni content higher by typically 2 to 3% than the parent metal.\(^{6}\) The low-energy processes accompanied with fast cooling rates, produce highly ferritic welds that reduce the impact toughness and ductility of the material.\(^{5}\) As a result, autogenous welding is not recommended particularly for electron beam and laser beam welds to be used in the as-welded condition.\(^{5}\) Furthermore, the proper ratio of \(\alpha/\gamma\) in the heat-affected zone (HAZ) of DSS welds can only be achieved by the proper selection of welding parameters and procedures, in which the post-weld heat treatment is included.\(^{6}\) The high cooling rate normally results in a high \(\alpha\) content in the HAZ. It was suggested that the \(\alpha\) content should be less than 75% in most applications.\(^{7}\) Simulation of thermal cycles in the HAZ of DSSs indicated that very rapid cooling results in no virtual reduction in toughness and a small reduction in pitting resistance.\(^{5}\) The addition of nitrogen in modern DSSs enhances the reformation of austenite in the HAZ to improve corrosion resistance and impact toughness of that region.\(^{5}\)

It is known that high strength steels are susceptible to hydrogen embrittlement (HE), which can induce premature failure of structural components. Cold cracking in the DSS weld containing \(\alpha\) in the range of 60 to 100% has been reported, and the susceptibility to hydrogen-assisted cracking of the weld metal increases with increasing the \(\alpha\) content.\(^{9}\) The effect of HE on DSS welds is of considerable interest and less research has focused on this area. The level of HE resistance of the material can generally be related to the...
fracture separation process, which in turn depends on the microstructure and the hydrogen concentration.\textsuperscript{10} In high strength steels, HE and stress corrosion cracking are overlapping processes.\textsuperscript{11} Hence, the resistance to hydrogen-induced crack becomes an important consideration for DSS welds to be used in hydrogen-containing environments.

The purpose of this investigation was to study the microstructure and some mechanical properties of 2205 laser welds produced with the addition of nickel powder to the weld pool. The flow rate of powder was so adjusted to obtain the weld metal having nearly the same $\alpha/\gamma$ ratio as the base material. In addition to the magnetic measurement of $\alpha$ content, impact tests of the welds at low temperatures were also employed to confirm that the proper $\alpha/\gamma$ ratio in the weld metal had been achieved. Notched tensile tests in hydrogen were performed on laser-welded specimens and the results were compared to those of the base material.

2. Experimental Procedures

The material used in this investigation was the SAF 2205 grade purchased from AVESTA, Sweden in the form of 3.2 mm thick plates. The as-received steel plates consisted of elongated and banded structures of $\alpha$ and $\gamma$ phases. The chemical composition in mass percent was 21.1 Cr, 5.8 Ni, 2.7 Mo, 0.052 C, 1.42 Mn, 0.45 Si, 0.025 P, 0.022 S, 0.02 Cu and balance Fe.

Laser welding was carried out using a Rofin-Sinar 850 5 kW CO$_2$ laser in the direction perpendicular to the rolling direction of the steel plate. Bead-on-plate laser welds were made with metal powder additions through a coaxial nozzle. Figure 1 shows the schematic diagram of a coaxial powder feed nozzle used in laser welding. Nickel powder (0.09 mass% Co, 0.01 mass% Fe, 0.03 mass% S and balance Ni.) with the particle size in the range of 45 to 75 $\mu$m was used in laser welding to modify the composition of the weld metal. The flow rate of nickel powder was controlled by a commercially available powder feeder using argon as the carrier gas. In welding, the laser power was kept constant at 3.2 kW and a travel speed of 800 mm/min was employed for all welds throughout the experiment. Full-penetration welds having a wine-glass weld profile were produced and all welds revealed no detectable defects in X-ray inspection carried out prior to mechanical evaluation. It is noted that the attached number behind laser-welded (LW) specimens represents the flow rate of nickel powder in gram per minute, e.g. the LW-3 specimen indicates the laser-welded specimen with a powder flow rate of 3 g/min.

The charpy test was used to estimate the impact toughness of the weld metal of DSS welds with or without powder additions. The subsize impact specimen (2.5 mm thick) according to ASTM E23-91 standard\textsuperscript{12} was employed in the test. The notch of impact specimens was located at the centerline of laser welds and the direction of the crack propagation was parallel to the weld direction. Impact tests were performed on both laser welded and unwelded specimens at the temperature range between room temperature and $-100^\circ$C.

Notched tensile test is known sensitive to the environmental change that leads to the reduced mechanical properties of the material. As a result, the double-edge notched specimen of 3 mm thickness was employed as shown in Fig. 2. To evaluate the effect of HE on notched tensile strength (NTS) of laser welds, notched tensile tests were conducted in an autoclave at room temperature with hydrogen pressure of $1 \times 10^6$ Pa (10 atm). A constant displacement rate of 0.0072 mm/min was chosen for all specimens to prolong the gas–metal interaction. The detailed procedures for notched tensile tests had been presented elsewhere.\textsuperscript{13} The result of notched tensile tests was the average of three specimens. The index of relative susceptibility to HE of various specimens was determined from the NTS loss, which can be expressed as follow:

$$\text{NTS loss (%) } = \frac{\text{NTS}_{\text{in Air}} - \text{NTS}_{\text{in H}_2}}{\text{NTS}_{\text{in Air}}} \times 100\%$$

Macroscopic observations of the entire fracture surface of specimens tested under various conditions were also conducted to compare the relative proportion of the slant and flat fracture regions. Additionally, the fracture surfaces of notched specimens after tensile testing were examined with a scanning electron microscope (SEM), with attention paid to the crack initiation site and the change of fracture modes.
3. Results and Discussion

3.1. Microstructural Examinations

Figure 3 is optical micrographs showing the structures in the weld metal of laser welds with varied nickel powder additions. The microstructure of the weld metal (254 Hv) in an autogeneous weld (the LW-0 specimen) comprises of mainly $\alpha$ phase and the less amount of intergranular $\gamma$ (grain boundary and Widmanstatten $\gamma$) and intragranular $\gamma$ as illustrated in Fig. 3(a). For laser welding with nickel powder additions, the $\gamma$ content in the weld metal increased as the powder flow rate increased. Figure 3(b) presents the microstructure of the weld metal (242 Hv) with a powder flow rate of 3 g/min, i.e. the LW-3 specimen, in which the reformation of $\gamma$ was quite extensive. The primary solidification occurred as delta ferrite, which made such a weld resistant to hot cracking. Increasing the powder flow rate to 5 g/min, the weld metal (the LW-5 specimen) became almost fully $\gamma$ as displayed in Fig. 3(c). Under this situation, the solidification occurred as primary austenite and the microstructure contained a small amount of delta ferrite. It is noted that the fully austenitic welds are sensitive to weldmetal solidification cracking and the strength of these welds was half of the DSS. The hardness in the weld metal of LW-5 specimens was 195 Hv, which was much lower than 240 Hv of the base metal. Due to low hardness of LW-5 specimens, no further evaluation of mechanical properties was performed on the weld metal produced at this flow rate.

The desired $\alpha/\gamma$ ratio or the $\alpha$ content in the weld metal could be experimentally determined. However, the flow rate of metal powder should be controlled within a certain range to avoid the excessive absorption of laser by powder during welding. The flow rate range of metal powder through the coaxial nozzle was dependent on the laser power and the specimen thickness. For instance, an increased laser power could allow a faster flow rate, while a thin specimen required slower flow rates of powder additions. Normally, a high flow rate of metal powder that is often used in cladding applications would reduce the penetration of laser welds significantly. As a result, only partial penetration welds could be obtained for excessive additions of powder at a given laser power, e.g. 8 g/min flow rate and 3.2 kW laser power in welding of 3.2 mm thick specimens.

The decrease in the $\alpha$ content of DSS welds with increasing the flow rate of nickel powder is clearly shown in Table 1 by using a ferrite scope. Although the determination of the $\alpha$ content in the weld metal by such a magnetic technique is simple and fast, the accuracy is not as good as quantitative image analysis. Due to the existence of preferred orientation of welded structures, the $\alpha/\gamma$ ratio as determined from their X-ray diffraction peaks was not suitable. It should be emphasized that a LW-3 specimen had the $\alpha$ content about 45 % in the weld metal, which was close to 42 % of the base material. The chemical compositions (mass%) determined by EDS analyses indicated that the weld metal consisted of approximately 21.7 Cr, 7.8 Ni, 1.1 Mn, 2.0 Mo, and 67.0 Fe, whereas the base metal comprised of 21.8 Cr, 5.8 Ni, 1.2 Mn, 1.8 Mo, and 68.8 Fe. The contents of the major alloying elements (Cr and Ni) of 2205 DSS were determined by EDS analyses within an accuracy of 3 %. Compositional analyse clearly demonstrated that the weld metal of LW-3 specimens had a nickel content higher by about 2 % than the base metal. It also confirmed that the weld metal of LW-3 specimens and conventional welds had a resembling Ni content. Consequently, a flow rate of 3 g/min was considered to be an appropriate flow rate for laser welding of 2205 DSS (3.2 mm thick) with 3.2 kW laser power and 800 mm/min travel speed. In fact, other combinations of welding parameters, e.g. 3.5 kW and 900 mm/min, could obtain similar welds by increasing the flow rate of Ni powder by approximately 1/8 as compared with the present investigation.

The foregoing discussion has been focused on the weld metal. However, the HAZ and the fusion boundary of laser welds are also important regions to be examined but with more difficulty to determine the $\alpha$ content. The low heat

Table 1. The contents of $\alpha$ and $\gamma$ phases observed in weld metals produced at various flow rates of nickel powder.

| Specimen | LW-0 | LW-3 | LW-5 | BM* |
|----------|------|------|------|-----|
| $\alpha$ (%) | 72   | 45   | 2    | 42  |
| $\gamma$ (%) | 28   | 55   | 98   | 58  |

* Base metal

Fig. 3. Optical photographs showing the microstructures in the weld metal of (a) LW-0, (b) LW-3, and (c) LW-5 specimens.
input (240 J/mm) of laser welds reduced the HAZ to a minimum width. Figure 4 displays the microstructures near the fusion boundary of LW-0 specimens, in which banded $\alpha + \gamma$ structures of the base metal can be observed in the lower right portion of the figure. The boundary between the high temperature HAZ and the weld metal in laser welds is quite difficult to distinguish as can be seen from Fig. 4. It is also evident that the grain size of the weld metal is considerably greater than the HAZ in laser welds. The $\alpha$ content near the fusion boundary could not be measured by a ferrite scope but it appeared to be more than that of the base metal. However, several reports on welding 2205 DSS with high energy density processes indicated no significant microstructural changes within the HAZ.14,15) Further studies regarding the detailed analysis of microstructures in the HAZ of such welds are needed.

### 3.2. Impact Tests

Table 2 lists the impact results of 2205 DSS and its laser welds tested at temperatures from room temperature to $-100^\circ$C. It indicated that the impact energy decreases with decreasing the test temperature slightly for the base material and LW-3 specimens, but noticeably for LW-0 specimens. At a test temperature of $-100^\circ$C, the base material and the LW-3 specimen could remain high impact energies (17 and 23 J, respectively), while the LW-0 specimen was considerably lowered (5 J). The results clearly demonstrated that the impact toughness of autogenous laser welds could be improved with the addition of nickel powder in laser welding at a test temperature of $-100^\circ$C.

The Charpy test is qualitative and often used as a material evaluator and separator.16) It was not the intention to study the ductile-to-brittle transition temperature (DBTT) curves of various specimens in this investigation. However, an obvious shift in the transition temperature could be seen in laser welds with nickel powder additions. The DBTT of LW-0 specimens was higher than that of both the base material and the LW-3 specimen. Apparently, the increased $\alpha$ phase of LW-0 specimens could be attributed to increased $\alpha$ content in the weld metal. The $\alpha$ content of LW-0 specimens was approximately 72%, which was considerably more than those of the base material and LW-3 specimen.

Figure 5 shows SEM fractographs of LW-3 and LW-0 specimens after impact tests at $-100^\circ$C. The fractograph of LW-3 specimens reveals extensive ductile dimple fracture as shown in Fig. 5(a), which is virtually the same as the base material tested at $-100^\circ$C. In contrast, the fracture surface of LW-0 specimens consists primarily of cleavage fracture with a small amount of dimples at grain boundaries as displayed in Fig. 5(b). Similar observations but with more dimples were observed for the same specimen tested at $-75^\circ$C. The impact-fractured surface exhibited mainly ductile fracture for all specimens tested at temperatures above $-50^\circ$C. Fractographic examinations are consistent with the impact results illustrated in Table 2. Accordingly, the impact test at low temperatures ($-75$ to $-100^\circ$C) along with the hardness test of laser welds could be used to determine whether a proper flow rate of metal powder was chosen in the process.

### 3.3. Notched Tensile Tests

The results of notched tensile tests in air and hydrogen for various specimens are shown in Fig. 6, in which the NTS loss of a given specimen is also included. It is known that the $\alpha$ phase is harder than the $\gamma$ phase in DSSs.17) Therefore, a higher $\alpha$ content in the structure led to a higher strength as well as NTS. As mentioned previously, the $\alpha$ contents of the base material and the LW-3 specimen were comparable, while the LW-0 specimen was considerably higher. The NTS of the LW-0 specimen in air, as expected, was higher than that of the base material and the LW-3 specimen. On the other hand, the $\gamma$ phase is more resistant to HE than the $\alpha$ phase in DSSs.18,19) The lack of $\gamma$ in LW-0 specimens led to an increased HE susceptibility. The NTS
of LW-0 specimens decreased from 945 MPa in air to 714 MPa in hydrogen, i.e. a NTS loss of 24.4%. On the contrary, the NTS of LW-3 specimens was 888 MPa in air and 864 MPa in hydrogen, corresponding to a NTS loss of 2.7% which was even lower than 6.7% of the base material (869 MPa in air and 811 MPa in hydrogen). These results clearly demonstrated that the addition of Ni powder to the weld pool could reduce the HE susceptibility of laser welds significantly. It also implied that a high \( \alpha \) content in the structure was detrimental to HE resistance of DSSs.

Fracture surfaces of notched tensile specimens tested in air, in general, consisted of slant fracture (SF) at near surface regions and flat fracture (FF) in the interior.\(^{20}\) The FF region represents loading under higher constraint and fractured in plain strain condition during tensile test, while the SF is deformed in plane stress condition.\(^{21}\) Figure 7(a) is a macroscopic photograph of the base material tested in air, showing two lenticular-shaped regions of SF surround triangular-shaped areas of FF. Figure 7(b) displays the macrograph of the base material tested in hydrogen, in which severe secondary cracks are observed in the FF region. It is noted that the increment of FF region in the fracture surface is also an indication of enhanced HE susceptibility. For specimens susceptible to HE, e.g. the LW-0 specimen, the fracture appearance exhibits only FF in hydrogen as shown in Fig. 7(c). In contrast, the LW-3 specimen was resistant to HE and has the fracture appearance as shown in Fig. 7(d), which is similar to Fig. 7(b) except the absence of secondary cracks. The banded structure of \( \alpha \) and \( \gamma \) in the DSS could provide fast diffusion paths for hydrogen in \( \alpha \) phase, leading to severe secondary cracks of the base material in the test. Figure 8 clearly indicates that secondary cracks are mainly along \( \alpha / \gamma \) boundaries in the base material. Such cracks were not found in the LW-3 specimen, implying the advantage of randomly distributed \( \alpha \) and \( \gamma \) phases in the weld metal.

At the same level of \( \gamma \) content, the LW-3 specimen exhibited a lower NTS loss than the base material in hydrogen. It is believed that hydrogen atoms diffuse much faster and are trapped much lesser in \( \alpha \) phase than in the \( \gamma \) phase.\(^{22}\) Trapping of hydrogen at the \( \alpha / \gamma \) interface in 22Cr-6Ni-3Mo DSS has been said to be the most significant factor to reduce diffusivity.\(^{23}\) The presence of mutual interlocking \( \alpha / \gamma \) phases in the weld metal of LW-3 specimens could be more effective to retard hydrogen diffusion inward, leading to a lower NTS loss and much less secondary cracks on the fracture surface.

It was reported that the FF region was affected mostly by hydrogen and often associated with a change in fracture modes.\(^{13,20,24}\) SEM fractographs of various specimens after notched tensile tests are given in Fig. 9. The fracture surface of the base material presents mainly ductile dimples in air, while quasi-cleavage with extensive secondary cracks is observed within the FF region as shown in the right half of Fig. 9(b) and dimple fracture, the left half of Fig. 9(b), is observed on the remaining FF region. Fractographic observations were in consistent with...
NTS losses of the base material and the LW-3 specimen in hydrogen. Apparently, the weld metal could have a better resistance to HE than the parent material if a proper ratio of \( \alpha/\gamma \) was achieved after welding. In case of LW-0 specimens, the fracture mode changes from dimple to cleavage as the environment altered from air to hydrogen as displayed in Figs. 9(c) and 9(d). The high \( \alpha \) content associated with autogenous laser welds was responsible for such changes, indicating the high susceptibility to HE of LW-0 specimens.

Due to the size limitation, mechanical properties of the HAZ of laser welds are difficult to carry out. Microhardness measurements on LW-3 specimens indicated that the hardness of the HAZ was 254 Hv, which was higher than the weld metal of 242 Hv and the base metal of 240 Hv. Conventional tensile tests of smooth LW-3 specimens in air and hydrogen (10 atm) at a strain rate of \( 5 \times 10^{-6} \) s\(^{-1} \) were also performed. The fracture location of tensile specimens was found within the base metal regardless the environment. This implied that the strength of 2205 DSS was not affected by laser welding and the HE was not observed in the weld metal or the HAZ for smooth specimens. Nevertheless, fracture along the weld interface was found for the same specimen tested in the saturated H\(_2\)S solution, suggesting that the HAZ or the region of microstructural discontinuity was susceptible to HE in a more aggressive environment. More work in this area is undertaken to evaluate the HE susceptibility of laser welds, especially in the HAZ region.

4. Conclusions

(1) It was possible to modify \( \alpha/\gamma \) ratio or the \( \alpha \) content in the weld metal of 2205 DSSs by adding Ni powder through a coaxial nozzle during laser welding. The \( \alpha \) content in the weld metal could be easily adjusted by the flow rate of nickel powder at given processing parameters. For example, a flow rate of 3 g/min was considered to be proper for welding of 3.2 mm thick DSS at the laser power of 3.2 kW and a travel speed of 800 mm/min.

(2) The base material with banded \( \alpha+\gamma \) structures was susceptible to HE and exhibited severe secondary cracks along \( \alpha/\gamma \) phase boundaries after notched tensile tests in hydrogen. In contrast, the LW-3 specimen with similar \( \alpha \) content to the base material was resistant to HE due to the random distribution of \( \alpha \) and \( \gamma \) in the weld metal.

(3) Autogenous laser welds were highly susceptible to HE as reflected by a NTS loss of 24.4%. The susceptibility to HE was significantly lowered in laser welds with nickel additions, e.g. 2.7% NTS loss of LW-3 specimens. Apparently, a higher volume fraction of \( \alpha \) was responsible for the higher susceptibility to HE of laser welds.

(4) The ductile-to-brittle transition temperature of 2205 laser welds could be notably reduced if a suitable amount of Ni powder was added in the welding process. Additionally, the impact test at low temperatures (\(-75 \) to \(-100^\circ\)C) together with the hardness test of laser welds could be used to check if the addition of nickel powder was proper in welding of 2205 DSS.

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