Laser Shock Peening of Duplex Stainless Steel in Comparison with Other Methods of Surface Treatment

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Duplex stainless steel (DSS) provides excellent mechanical strength and corrosion resistance and its application has been expanding to diverse industrial fields where strong corrosion resistance and mechanical strength are simultaneously desired. For the enhancement of surface hardness and wear resistance of DSS, various surface treatment techniques have been adopted previously, which however produced mostly minor improvement of corrosion resistance or occasional degradation of corrosion behavior. In this study, the results of laser shock peening of DSS are presented in comparison with those of previously attempted methods. It was demonstrated that the surface hardness, wear resistance, and corrosion resistance of DSS can be simultaneously increased by properly applied laser shock peening process. The maximum surface hardness enhancement of 29%, wear volume decrease of 66%, and corrosion rate decrease of 74% were achieved by water immersion type laser shock peening and similar results were also obtained by nozzle type laser shock peening.

Key Words: Laser shock peening, Surface treatment, Duplex stainless steel, Wear resistance, Corrosion resistance

1. Introduction

Duplex stainless steel (DSS) has been widely used in industrial fields that require high corrosion and wear resistances such as oil and gas, desalination, flue gas desulfurization, architecture, pulp and paper, food and drink industries.1,2 Most industrial grade DSS have microstructures with nearly equal fractions of ferrite and austenite, which provides superior corrosion resistance to other types of stainless steels, especially in chloride environments. DSS also has excellent mechanical properties such as high yield strength, good ductility and toughness as summarized in Table 1.3

Despite the excellent properties of DSS, there have been numerous studies to improve surface mechanical properties of DSS often for the enhancement of wear resistance or fatigue strength. The surface treatment techniques of DSS could be classified into three main categories: 1) thermal treatment without adding elements, 2) surface coating techniques with coating particles such as tungsten carbide or cobalt chrome alloy, and 3) surface residual stress enhancement using mechanical shock pressure. A successful application of these processes requires careful control of the process conditions since otherwise they can result in a loss of the original beneficial properties of DSS. Thermal treatment of DSS has been extensively investigated and many publications are available.3-5 Surface coating also has been frequently investigated since mid-1990’s.6-9 For surface residual stress enhancement by mechanical shock, shot peening (SP) or laser shock peening (LSP) is available. Although the history of SP of DSS dates back to 1995,10 most research works for SP of DSS have been published in recent years.11-14 Despite the reported effectiveness of LSP on the improvement of mechanical, fatigue, and corrosion properties of other metal alloys or stainless steels,15-19 LSP of DSS has not been investigated until recently. The authors reported the enhancement of surface hardness, wear resistance, and corrosion resistance of 2205 DSS by water immersion type LSP.20,21 Rubio-Gonzalez et al.22 investigated the effects of LSP on fatigue crack growth of DSS. These recent studies for LSP of DSS demonstrated that LSP could be an effective method to achieve a simultaneous improvement of hardness, wear resistance, and corrosion resistance of DSS.

In this paper, the results of two different types of LSP are presented and the effectiveness of LSP on the improvement of surface properties of DSS is compared with other methods of surface treatment. The degree of property enhancement achievable by each technique and its strengths and drawbacks are discussed.

| Table 1 Mechanical properties of 2205 DSS.22 |
|---------------------------------------------|
| Yield strength | 450 MPa |
| Tensile strength | 655 MPa |
| Elongation | 25% |
| Hardness | 270 HV (annealed) |
| Density | 7800 kg/m³ |
| Young’s modulus | 200 GPa |
| Annealing temperature | 1040 °C (Minimum) |
2. Surface treatment methods

2.1 Thermal treatment

The major objective of thermal treatment is to maintain or restore the phase balance between ferrite and austenite within DSS. For the fabrication of DSS plates or sheets, the material typically undergoes hot rolling and annealing procedures followed by cold rolling and annealing. After the hot forming process, DSS needs to be annealed to dissolve intermetallic precipitates and restore the mechanical properties and corrosion resistance, and the annealing temperature should be above 1040 °C for the 2205 DSS. To attain an enhanced surface hardness, additional heat treatment can be done at lower temperatures, which must be carried out at the conditions to avoid the formation of undesirable precipitations since the precipitation of undesirable secondary phases can result in a serious loss of mechanical strength and corrosion resistance. Although a large number of publications about heat treatment and its effects on the metallurgical characteristics of DSS are available, it is beyond the scope of this paper to review the metallurgical properties of DSS. Instead, this paper focuses on the change of mechanical and corrosion properties only as a result of heat treatment.

2.2 Surface coating

In surface coating techniques, additional elements such as metal, ceramic, or nitrogen are deposited or injected into the surface layer using thermal energy or momentum. Plasma or laser processes are typically applied for the surface coating. Ceramics are mostly added to the surface layer in order to enhance surface hardness and wear resistance. The addition of nitrogen can lead to the formation of so called S-phase, which is known to improve the surface hardness and wear resistance. Metal elements are also added during welding of DSS to restore the phase balance destroyed in the weld and heat affected zone. Depending on the surface coating methods, the resulting surface properties can differ completely and the coating components can locally alter the original material properties, often in negative ways.

2.3 Peening

Unlike the thermal treatment or surface coating techniques which cause the change of metallurgical phase or chemistry of DSS, peening is a mechanical process to generate plastic deformation of the material close to the surface which in turn induces a compressive residual stress in the peened layer. SP process uses a mechanical impact of a metal ball to induce the deformation, whereas an intense plasma pressure generated by a short laser pulse induces a shock wave and plastic deformation in LSP process.

Figure 1 shows the schematic diagram of LSP. A high power pulsed laser, typically a nanosecond Nd:YAG or Nd: Glass laser, irradiation on the coated or uncoated metal surface results in the generation of a rapidly expanding plasma plume which exerts an intense pressure on the metal surface. In order to confine the plasma pressure on the metal surface, the workpiece is often immersed in water as shown in Fig 1(a), water immersion type LSP, or water is sprayed over the surface using a nozzle as shown in Fig 1(b), nozzle type LSP. It is known that a few millimeter thick water layer is sufficient for the confinement of plasma pressure. Previously, we reported the results of water immersion type LSP on the enhancement of hardness, wear resistance, and corrosion resistance of DSS. In the present study, we also present the results of nozzle type LSP of DSS. LSP can be done without a coating material, typically a thin metal foil or paint. Metal foil coating can not only protect the ablative damage of irradiated surface but also increase the shock pressure applied on the workpiece via impedance mismatch effect. Paint is mostly used to reduce reflection loss of incident laser light at the metal surface.

3. Results and Discussion

The major interest in surface treatment of DSS is the improvement of surface hardness, wear resistance, corrosion resistance, and fatigue property. In the following, the effects of LSP on these properties are presented and compared with those of other techniques.

3.1 Surface hardness and Wear resistance

In Fig. 2, the degree of surface hardness increase achieved by various surface treatment methods is presented. Previously, we reported that the maximum increase of surface hardness achieved by water immersion type LSP was about 29% (optimum conditions: Nd: YAG laser, wavelength = 532 nm, pulse duration = 8 ns, flat top profile, laser irradiance = 10 GW/cm², spot diameter = 1.5 mm, pulse density = 75 pulse/mm², protective coating = 100 μm Al foil). With the nozzle type LSP (using the same laser), we obtained about 25% enhancement in Vickers hardness (Akashi, HM-112, 1 kg load for 10 s) at the conditions of laser irradiance = 10 GW/cm², spot diameter = 1.2 mm, pulse density = 10 pulse/mm², protective coating = 100 μm Al foil. Note that the laser beam with an original diameter of 11 mm was focused using a plano-convex lens (f = 128 mm) to 1.2 mm which was measured...
with a calibrated CCD camera. At the laser irradiance level adopted in this experiment, the plasma pressure was expected to be over 5 GPa according to the formula by Berthe et al.\textsuperscript{30} but was not directly measured. The nozzle type LSP experiments were repeated on four different DSS samples and the average increase of surface hardness is provided above. Note that the process speed can be significantly increased using the nozzle type LSP with minor decrease of surface hardness due to the reduced pulse density. In addition, the nozzle type LSP is less limited by the size of workpiece and thus can be applied more flexibly. On the other hand, Rubio-Gonzalez et al.\textsuperscript{22} reported that no surface hardness increase was achieved during their LSP experiment of DSS without protective coating. The authors explained that it was possibly due to insufficient laser irradiance. It also could be due to the ablation of metal in the absence of protective coating.

The reported surface hardness increase of DSS by SP varied over a wide range from less than 10%\textsuperscript{12} to over 130%.\textsuperscript{13} A conspicuous difference between LSP and SP is the hardening depth. Figure 3 shows the Vickers hardness profiles along the depth of the four DSS samples treated by nozzle type LSP, demonstrating that the hardening depth reached nearly 2 mm from the surface. Almost the same hardening depth was obtained by water immersion type LSP.\textsuperscript{30,31} In contrast, the hardening depth achieved by SP was merely about 0.2–0.3 mm.\textsuperscript{21,22}

As shown in Fig. 2, the highest surface hardness enhancement, up to about 300% or higher, was achieved by thermal spray coating of WC-based ceramic particles\textsuperscript{6,20} or plasma nitriding.\textsuperscript{7,31} For WC particles coating, various matrix compositions were attempted, for example, 50(WC + 12Co)-balanceNi\textsubscript{9}Cr\textsubscript{2}Si\textsubscript{3}·5Fe\textsubscript{2}B\textsubscript{0.5}C and 83WC\textsubscript{10}Co\textsubscript{4}Cr\textsubscript{0.5}, 86WC\textsubscript{13}Co\textsubscript{4}Cr, 83WC\textsubscript{10}Co\textsubscript{4}Cr\textsubscript{0.5}, 90WC\textsubscript{10}Co, 86WC\textsubscript{13}Co\textsubscript{4}Cr, 83WC\textsubscript{13}Co\textsubscript{4}Cr,\textsuperscript{7} and it was shown that the matrix composition was critical in determining the properties of coated layer. Direct injection of WC particles into a laser remelted layer was also tried.\textsuperscript{21} Plasma nitriding was carried out either in pure N\textsubscript{2}\textsuperscript{7} or N\textsubscript{2} + H\textsubscript{2}\textsuperscript{31} environments. Nagatsuoka et al.\textsuperscript{31} reported that active screen plasma nitriding process produced superior results to direct plasma nitriding. Alternatively, it was reported that the annealing of rolled DSS at temperatures below 875 °C resulted in the improvement of hardness and strength but the reduction of ductility, impact toughness, and corrosion resistance.\textsuperscript{23}

Surface hardness is closely related to the wear characteristics of the material. We reported that the wear volume of peened DSS decreased by 66% from that of unpeened DSS when water immersion type LSP was applied at optimum conditions.\textsuperscript{22} Figure 4 shows the wear volume measured on the four different DSS samples treated by nozzle type LSP. Wear volumes of all the peened samples decreased significantly (57% in average) and the results are reproducible. The enhanced surface hardness by other methods also was typically accompanied by increased wear resistance.\textsuperscript{6,7,31} However, a number of studies reported that the inherent high corrosion resistance of DSS could be degraded if the process conditions were inappropriate, irrespective of the increase of wear resistance, which will be discussed in detail later.

### 3.2 Compressible residual stress

The fatigue life of metallic components subject to cyclic loads can be significantly extended by generating compressible residual stress. Peening is the only applicable method to generate compressible residual stress among the surface treatment techniques discussed in this study. Figure 5 shows the residual stress profiles in DSS achieved by LSP in comparison with that of unpeened sample. Residual stress measurement was carried out with standard X-ray diffraction technique using Cr-K\textsubscript{α} radiation. The residual stresses along the depth were measured by electropolishing the sample with 100 μm step.\textsuperscript{22} The compressible residual stress at the laser shock peened surface increased almost three folds. Both water immersion type and nozzle type approaches were found to produce nearly the same results. Rubio-Gonzalez et al.\textsuperscript{22} reported that LSP reduced fatigue crack growth of DSS and
increased fracture toughness. On the other hand, the maximum compressible residual stress achievable by SP was reported to be greater than that of LSP as shown in Fig. 6.11 However, the thickness of surface layer subject to compressible residual stress achievable by SP was much shallower, about 0.3 mm, than that by LSP, about 0.8 mm.

3.3 Corrosion resistance

The high corrosion resistance of DSS is often the most critical factor in determining DSS as the metal of choice in many applications. DSS is far more resistant to chloride stress corrosion cracking than austenitic stainless steel types 304 and 316.11 Previously, we reported11 that the corrosion rate of DSS estimated by potentiodynamic polarization test was reduced by 74% from that of unpeened material and the number and size of corrosion pits produced after copper accelerated acetic acid salt spray (CASS) test were significantly reduced. For DSS peened by nozzle type LSP, the potentiodynamic polarization test was performed on three samples in 0.35 wt% NaCl solution for 120 min with nitrogen injection in accordance to the ASTM G5 (2004) as in the immersion type samples.12 except surface polishing. Although ASTM G5 requires the sample polished with 2000-grit SiC sand paper prior to the corrosion test, we intentionally skipped this step in order to examine the corrosion characteristics of peened surface more directly. The corrosion rates estimated from the potentiodynamic polarization test results were 2.74, 1.53, 6.59 mm/year while that of the unpeened sample was 10.39 mm/year. The wide variation of corrosion rates among the peened samples is considered to be attributed to the skip of polishing step. The average reduction of corrosion rate of the peened samples is about 65%. Figure 7 shows the CASS test results of DSS peened by nozzle type LSP in comparison with the unpeened one. Since the CASS test took too long until corrosion pits developed on the DSS samples with smooth surfaces, regardless of being peened or unpeened, the CASS test was conducted using the wear test samples because corrosion pits developed faster on the wear tracks and thus clearer comparison was possible. After 480 hours of CASS test, the surface of peened sample revealed no difference, whereas clear evidences of corrosion development were observed on the unpeened sample surface.

The corrosion characteristics of DSS were known to be sensitively affected by the surface treatment procedures applied to the material. Bjordal et al.30 reported that thermal spray coating of WC particles on DSS with pure Co as the binder resulted in a strong synergetic effect where corrosion of the binder itself lead enhancement of erosion. Neville and Hodg-kiess32 also reported that the extent and mechanisms of corrosion of thermal spray coated DSS strongly depended on coating types adopted in their study, 86WC-10Ci-4Cr and 50WC-50Ni-Cr-B-Si. Kliauga and Pohl31 investigated the influence of process temperature on the nitride layer and bulk material during plasma nitriding of DSS. They reported that little change of corrosion resistance was observed when the process temperature was kept at 350 °C. However, the sample nitrided at 400 °C resulted in a significant decrease in the pitting corrosion resistance. Similar results were also reported by Blawert et al.31 from the study of plasma immersion ion implantation of DSS. They obtained the best wear resistance from the DSS treated at the temperature of 500 °C which, however, revealed a drastic decrease of corrosion resistance. Contrary, the sample treated at 400 °C was reported to preserve the original corrosion property with moderate improvement of wear resistance.

The results from these previous studies suggested that the coating of WC particles or nitriding of DSS could be effective on the improvement of surface hardness or wear resistance. However, these processes are not much effective in improving the corrosion resistance of DSS. Most authors reported that only minor improvement or no decrease of corrosion resistance was observed when the treatment was applied at optimum conditions. On the contrary, they noted that the inherent strong corrosion resistance of DSS could be seriously degraded by inappropriately determined process conditions, such as by the change of binder material composition or by a few tens of degree difference in process temperature.

4. Summary

The surface treatment techniques to be applied for the enhancement of abrasion or corrosion resistance of DSS are discussed in comparison with the results from LSP. It was shown

Fig. 6 Magnitude of compressible residual stress and its depth achieved by LSP and SP processes.

Fig. 7 Scanning electron micrographs of the (a) peened by nozzle type LSP and (b) unpeened DSS samples after 480 h of CASS test.
that the water immersion type and nozzle type LSPs produce nearly the same property enhancement effects on DSS. Thus, both LSP approaches may be adopted for the convenience of application procedures rather than by the consideration of their effectiveness. The reported results of different surface treatment techniques, especially the surface coating methods, showed that they could produce contradicting effects in the wear and corrosion behaviors, that is, an enhancement of wear resistance at the expense of corrosion resistance. On the other hand, the present study clearly demonstrated that the enhancement of surface hardness, wear resistance, and corrosion resistance of DSS can be accomplished simultaneously by applying LSP only.

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References

1) TMR Stainless: Practical guidelines for the Fabrication of Duplex Stainless Steel 2nd ed. (International Molybdenum Association, London, 2009).
2) J. Charles: Steel Research International 79 (2008) 455.
3) K. L. Weng, H. R. Chen, and J. R. Yang: Mat. Sci. Eng. A 379 (2004) 119.
4) K. Vijayalakshmi, V. Muthupandi, and R. Jayachitra: Mat. Sci. Eng. A 529 (2011) 447.
5) Q. Ran, Y. Xu, J. Li, J. Wan, X. Xiao, H. Yu, and L. Jiang: Mat. Design 56 (2014) 959.
6) A. Dwars, W. Kochanowski, B. schramm and F. Sehr: Mat. Corrosion 59 (2008) 870.
7) A. M. Kliauga and M. Pohl: Surface and Coatings Tech. 98 (1998) 1205.
8) C. Blawert, A. Weisheit, B. L. Mordike, and F. M. Knoop: Surface and Coatings Tech. 85 (1996) 15.
9) A. M. Do Nascimento, V. Ocelik, M. C. F. Ierardi, and J. Th. M. De Hosson: Surface and Coatings Tech. 202 (2008) 2113.
10) Y. F. Al-Obaid: Engineering Fracture Mechanics 51 (1995) 19.
11) P. Sanjuro, C. Rodríguez, I. F. Pariente, F. J. Belzunce, and A. F. Canteli: Procedia Engineering 2 (2010) 1539.
12) E. Real, C. Rodríguez, F. J. Belzunce, P. Sanjuro, A. F. Canteli and I. F. Pariente: Fatigue & Fracture of Eng. Mat. & Structures 32 (2009) 567.
13) Q. Feng, X. Wu, C. Jiang, Z. Xu, and L. Wu: JIMEPEG 22 (2013) 2905.
14) Q. Feng, C. Jiang, and Z. Xu: Mat. Design 47 (2013) 68.
15) P. Peyre, C. Carboni, P. Forget, G. Beranger, C. Lemaître, and D. Stuart: J. Mat. Sci. 42 (2007) 6866.
16) Y. Sano, M. Obata, T. Kubo, N. Mukai, M. Yoda, K. Masaki, and Y. Ochi: Mat. Sci. Eng. A 417 (2006) 334.
17) Y. Sano, T. Adachi, K. Akita, I. Altenberger, M. A. Cherif, B. Scholtes, K. Masaki, Y. Ochi, and T. Inoue: Key Eng. Mat. 345-346 (2007) 1589.
18) B. N. Mordyuk, Yu. V. Milman, M. O. Iefimov, G. I. Prokopenko, V. V. Silberschmidt, M. I. Danylenko, and A. V. Kotko: Surface and Coatings Tech. 202 (2008) 4875.
19) C. S. Montross, T. Wei, L. Ye, G. Clark, and Y.-W. Mai: Int. J. Fatigue 24 (2002) 1021.
20) H. Lim, M. Lee, P. Kim, J. Park, and S. Jeong: Desalination and Water Treatment 15 (2010) 43.
21) H. Lim, P. Kim, H. Jeong, and S. Jeong: J. Mat. Process. Technol. 212 (2012) 1347.
22) C. Rubio-González, C. Felix-Martínez, G. Gomez-Rosas, J. L. Ocaña, M. Morales, and J. A. Porro: Mat. Sci. Eng. A 528 (2011) 914.
23) G. Fargas, M. Anglada, and A. Mateo: J. Materi. Process. Tech. 209 (2009) 1770.
24) V. Muthupandi, P. Bala Srinivasan, S. K. Seshadri, and S. Sundaresan: Mat. Lett. 59 (2005) 2305.
25) R. Fabbro, P. Peyre, L. berthe, and X. Scherpereel: J. Laser Appl. 10 (1998) 265.
26) P. Peyre, R. Fabbro, P. Merrien, and H. P. Lieurade: Mat. Sci. Engineering A210 (1996) 102.
27) C. S. Montross, T. Wei, L. Ye, G. Clark, and Y.-W. Mai: Int. J. Fatigue 24 (2002) 1021.
28) A. D. chijioke, W. J. Nellis, and I. F. silvera: J. Appl. Phys. 98 (2005) 073526.
29) L. Berthe, R. Fabbro, P. Peyre, L. Tollier, and E. Bartnicki: J. Appl. Phys. 82 (1997) 2826.
30) M. Bjordal, E. Bardal, T. Rogne, and T. G. Eggen: Wear 186-187 (1995) 508.
31) K. Nagatsuka, A. Nishimoto, and K. Akamatsu: Surface & Coatings Tech. 205 (2010) S295.
32) A. Neville and T. Hodgkiss: Surface Eng. 12 (1996) 303.