

ICM11

Laser welding of Al-Si coated hot stamping steel

C. Kim^{a*}, M. J. Kang^a, Y. D. Park^b

^a*Korea Institute of Industrial Technology, 7-47 Songdodong Yeonsugu, Incheon 406-840, South Korea*

^b*Dong-Eui University, 995 Eomgwangno Busanjinju, Busan 614-714, South Korea*

Abstract

Advanced high strength steel (AHSS) is being increasingly used in automotive industries for weight reduction purposes. Hot stamping steel, which is a boron alloyed steel, has a strength greater than 1500 MPa after hot forming and successive quenching. Because the heating temperature is normally greater than 900 °C, a thin Al-Si based coating layer is applied to the steel surface to prevent oxidation. In this study, metallurgical characteristics of laser weldments were investigated in hot stamping steel plates with and without an Al-Si coating layer. The behavior of the Al-Si coating layer after the hot stamping process was analyzed, and the effects of Al-Si coating on laser weldability were investigated. Keyword : Al-Si coated steel; Boron-alloyed steel; Laser welding

© 2011 Published by Elsevier Ltd. Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).
Selection and peer-review under responsibility of ICM11

Keywords: Al-Si coated steel; Boron-alloyed steel; Laser welding

1. Introduction

In the past decade, extensive studies have been conducted to investigate the laser welding of advanced high strength steel (AHSS) used in light weight vehicles [1-9]. Dual-phase steel, transformation-induced plasticity steel, complex-phase steel, Martensitic steel, boron alloy steel, and new phase steel have been developed to meet demands for steel with higher strength. AHSS has higher strength and normally less favorable formability than conventional mild steel. Boron alloy steel such as 22MnB5 steel has a fully martensitic microstructure and the highest strength among commercialized AHSSs used in the automotive industry. To overcome poor formability, boron alloy steel is formed through a hot forming process at a temperature greater than the A_{C3} temperature and is thus referred to as hot forming steel. Various coatings such as Al-Si and Zn coatings have been investigated to prevent surface oxidation during the high-temperature process. Because Al-Si coating exhibits high oxidation resistance at high temperature [10-12], it has been more widely used than Zn coating, which has a melting temperature of 400 °C.

During laser welding of hot forming steel with an Al-Si coating, the coating is diluted into the weld zone, which results in Fe-Al intermetallic phase formation [13]. The brittleness of the Fe-Al intermetallic phase weakens the strength of the weld joint. According to a recent study conducted by the authors of the present paper, degradation of weldments is more important in an overlap welded joint than in a butt welded one [14]. In this study, laser overlap welding was conducted on hot stamping steel, 22MnB5, with and without Al-Si coating. The behavior of the Al-Si

* Corresponding author. Tel.: +82-32-850-0222; fax: +82-32-850-0210.
E-mail address: chkim@kitech.re.kr.

coating inside the welds was investigated, and the mechanical behavior of the weldments was analyzed.

2. Experimental setup

A fiber laser with a maximum output power of 3 kW and a 6-axis robot were used to implement laser welding, as shown in Fig 1. A laser beam was delivered through an optical fiber with a diameter of 200 μm and an optic system with a focal length of 300 mm.



(a) Fiber laser



(b) Laser optic and welding robot

Fig. 1 Laser welding system

The base material was hot forming steel, 22MnB5, with a thickness of 1.6 mm, and specimens of Al-Si coated and non-coated hot forming steel were prepared. The thickness and composition of the Al-Si coating layer were measured through scanning electron microscopy. The scales that formed on both surfaces of the non-coated hot forming steel during the hot forming process were mechanically removed before laser welding.

The laser welding was conducted on an overlap joint using a laser power of 3 kW and a welding speed of 3 m/min to achieve fully penetrated beads. The delivered laser beam was perpendicularly irradiated on the specimen with a beam diameter of 0.36 mm at the focal point (Fig. 2).

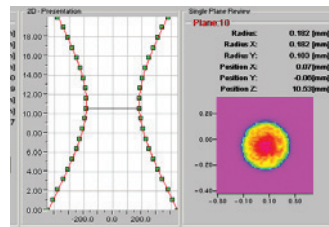


Fig. 2 Measured beam profile and diameter

Tensile shear tests were conducted three times on rectangular specimens with a width of 25 mm under each condition, and the average strength was used to compare the strength under both coating conditions. The micro-Vickers hardness of the samples was measured on 2% nital-etched weldments under a load of 100 gf, which was held for 10 s. In addition, 2% nital-etched weldments were observed using an optical and a scanning electron microscope (SEM).

3. Results and Discussion

3.1. Behavior of Al-Si coating layer after hot forming process

The magnified image and chemical composition of the Al-Si coating layer after the hot forming process, are shown in Fig. 3. During heat treatment, Al-Si coating was diffused to the base metal and the average thickness of the layer increased from 25 μm to about 35 μm . The aluminum content in the vicinity of the base metal abruptly decreased. At point 5 in Fig. 3, the Fe-Al intermetallic phase (IMP) was confirmed and the IMP layer was uniformly established with a thickness of 5 μm . Inside the coating layer, several cracks were found owing to the difference in thermal expansion coefficients of aluminum and steel, which agreed with observations made in a previous study [15].

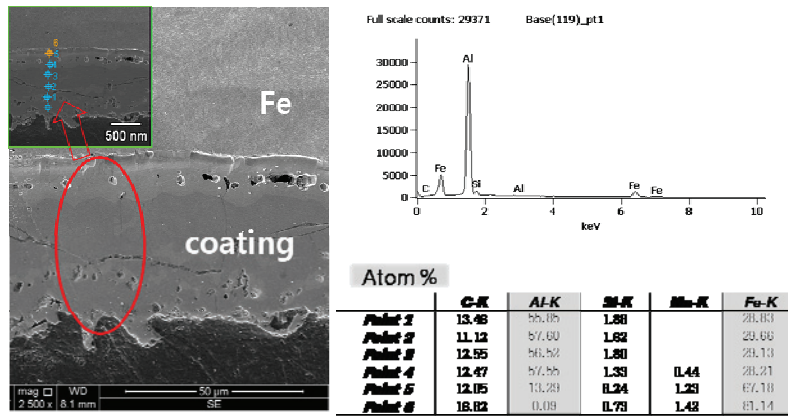


Fig. 3 SEM image and chemical composition of Al-Si coating layer

3.2. Welded specimen

Fig 4 shows cross-sections of the weldments and fracture modes for the tensile shear test. A “white band” layer was found in the middle of the heat affected zone (HAZ). The metallurgical aspect of this layer will be discussed in the next paragraph. In the case of the non-coated hot forming steel, failure occurred at the interfacial surface, while failure occurred along the fusion line in the case of Al-Si coated steel. The tensile shear strengths of non-coated steel and Al-Si coated steel were 17.3kN and 13.4kN, respectively. For Al-Si coated steel, an FeAl intermetallic phase developed during welding. This phase influenced the morphology of weldments as discussed in detail in the SEM-EDS section of the results.

The micro-Vickers hardness profiles are shown in Fig. 5. In both cases, similar hardness profiles were observed, with the fusion zone having the highest hardness and the heat affected zone having a lower hardness than the base metal. The HAZ inside the white band (inner HAZ) had relatively high hardness, while the HAZ outside the white band (outer HAZ) had extremely low hardness.

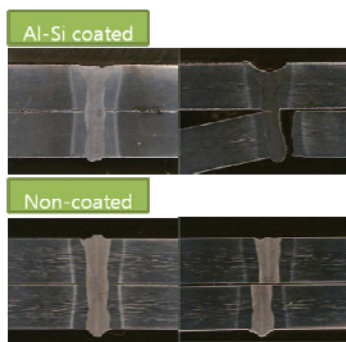


Fig.4 Macro section and fracture location

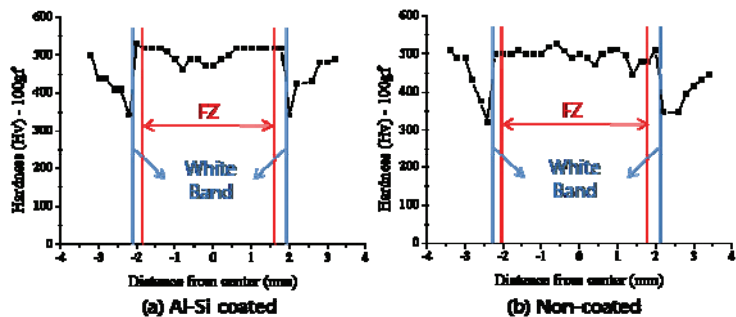


Fig.5 Hardness profiles of specimen

The microstructures of weldments were observed using an optical microscope; these microstructures are shown in Fig. 6. Heat input during the welding process transforms the martensite structure in the base metal. In the outer HAZ (Fig. 6a), the maximum temperature during the thermal cycle is lower than the phase transformation temperature, A_{C3} , which resulted in the formation of tempered martensite with relatively low hardness. The white band area (Fig. 6b) was heated to a temperature between A_{C3} and A_{C1} , which produced a bainitic microstructure. The inner HAZ (Fig. 6c) was heated to a temperature between A_{C1} and the melting temperature, which resulted in the formation of a mixed structure made of martensite and bainite. At the fusion zone (Fig. 6d), the melting and the successive quenching afforded a martensitic microstructure. A more detailed description of the structure distribution was observed upon SEM analysis, as shown in Fig. 7. It should be noted that the lath of martensite in the fusion

zone is longer and larger than that in the base metal. This can be explained by the expansion of the prior austenite grain boundary in the fusion zone owing to the recrystallization of austenite.

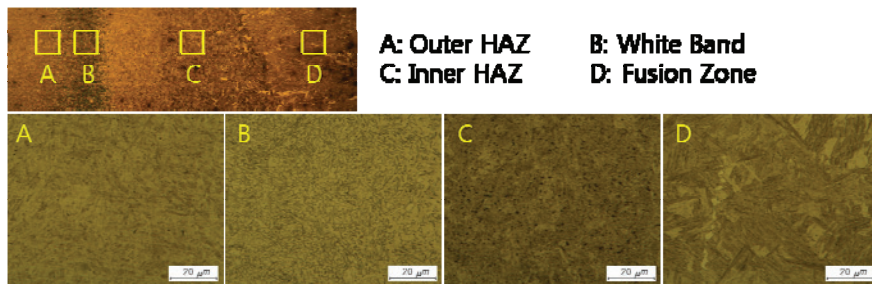


Fig. 6 microstructure of weldments

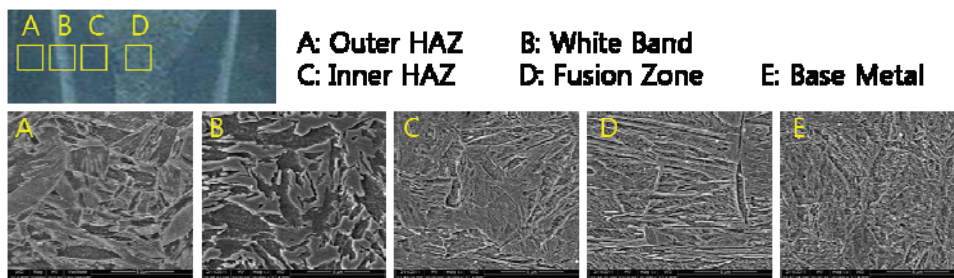


Fig. 7 SEM results for weldments

Although laser welding is a very low heat input process, HAZ softening was observed because the martensitic microstructure in the HAZ area was transformed into tempered martensite and bainite by heat input. However, as in the tensile shear test results shown in Fig. 4, the fracture did not occur along HAZ, but at the interfacial surface or along the fusion line. In the case of non-coated hot forming steel, stress is concentrated on a narrow interfacial bead with a width that is relatively small as compared to the width of the specimen, owing to the small beam diameter of the laser and high energy density (Fig. 8a). In the case of Al-Si coated hot forming steel, the Fe-Al intermetallic compounds were formed along the fusion line and a fracture occurred along the precipitate layer (Fig. 8b).

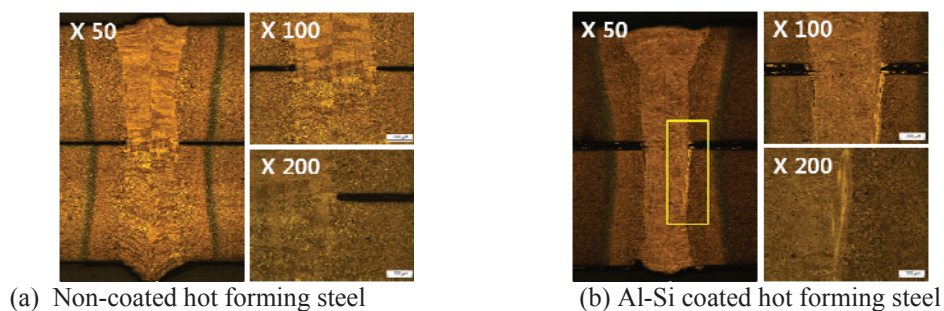


Fig. 8 Optical Microscope of weldments

SEM-EDS analysis was conducted to investigate the chemical composition of the intermetallic precipitate layer along the fusion line shown in Fig. 8b. The intermetallic precipitates were found to be three phase compounds composed of Fe, Al and Si (Fig. 9). A possible explanation for these findings is that the aluminum and silicon in the Al-Si coating had melted and were diluted into the weld metal during welding. While not being sufficiently stirred, some of these metals combined with Fe to produce an intermetallic phase that forms as layer along the fusion line during the cooling stage. Figure 9 shows the element analysis results for Al, Si, and O, obtained using an electron probe micro-analyzer. Aluminum and silicon consisting of the coating are soluble in Fe and homogeneously distributed inside the fusion zone but partially precipitated as an intermetallic phase rather than as a solid solution.

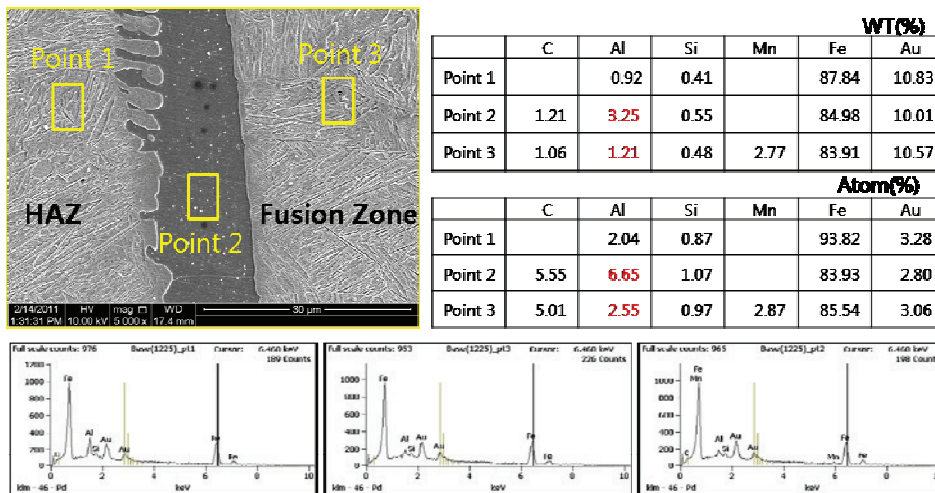


Fig.9 Analysis of precipitates

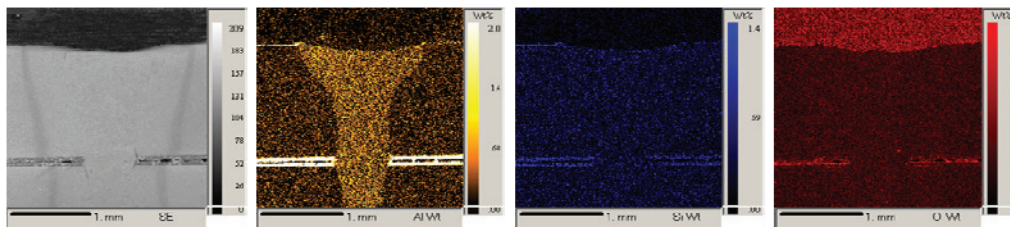


Fig.10 Elements distribution in weldments

4. Conclusion

In this study, the effects of Al-Si coating on laser weldability were investigated for Al-Si coated and non-coated hot forming steel. The conclusions of this study can be summarized as follows:

- 1) During the hot forming process, Al-Si coating was diffused into the base metal and the thickness of the coating increased from 25 μm to 35 μm.
- 2) In the heat affected zone, the martensitic microstructure was transformed into tempered martensite, bainite, and a mixture of bainite and martensite, on the basis of the location. The most softened area was the outer HAZ outside the white band, which consisted of tempered martensite.
- 3) The fracture location in the tensile shear test was propagated along the interface or fusion line rather than the softened HAZ because of stress concentration and brittle intermetallic precipitates.
- 4) Aluminum and silicon in the Al-Si coating were primarily dissolved into weldments as solid solution and partially developed as an inter-metallic phase with Fe. The inter-metallic phase precipitated along the fusion line, which weakened the strength of the weldments.

Acknowledgements

The authors wish to acknowledge Dr. Y.-R. Cho of POSCO for his help in preparation of specimen and helpful discussions.

References

- [1] Pieters RRGM, Krasnoperov MY, Richardson IM. Laser welding of high strength steels. *Proceeding of 22nd International Congress on Applications of Lasers & Electro-Optics*. Jacksonville, Florida, US; 2003, p. 294-303.
- [2] Liu Z, Kutsuna M, Xu G. Fiber laser welding of 780MPa high strength steel. *Proceeding of 25th International Congress on Applications of Lasers & Electro-Optics*. Scottsdale, Arizona, US; 2006, p.562-568.
- [3] Shi SG, Westgate S. Fiber-delivered laser welding of ultra-high strength steels for automotive applications, *TWI Report*. The Welding Institute; 2007, Report No. 865/2007.
- [5] Kang CY, Han TK, Lee BK, Chin GG. Hardness of laser welded AHSS with a strength over 600MPa for automotive. *Proceedings of 4th International Congress on Laser Advanced Materials Processing*. Kyoto, Japan; 2006, Paper No. 06-276.
- [6] Haferkamp H, Meier O, Harley K. Laser Beam Welding of New High Strength Steels for Auto Body Construction. *Key Eng Mater* 2007; **344**: 723~730.
- [7] Xia MS, Kunts ML, Tian ZL, Zhou Y. Failure study on laser welds of dual phase steel in formability testing. *Sci Technol Weld Joining* 2008;**13**:378-386.
- [8] Xia M, Biro E, Tian Z, Zhou YN. Effects of heat input and martensite on HAZ softening in laser welding of dual phase steel. *ISIJ Int* 2008;**48**:809-814.
- [9] Kim CH, Choi JK, Kang MJ, Park YD. A study on the CO₂ laser welding characteristics of high strength steel up to 1500MPa for automotive application. *J Achiev Mater Manuf Eng* 2010;**39**:79-86.
- [10] Senuma T. Physical metallurgy of modern high strength steel sheets. *ISIJ Int* 2001;**41**:520-532.
- [11] Maggi S, Murgia M. Introduction to the metallurgic characteristics of advanced high-strength steels for automobile applications. *Weld Int* 2007;**22**:610-618.
- [12] Karbasian H, Tekkaya AE, A review of hot stamping. *J Mater Process Technol* 2010;**210**:2103-2118.
- [13] Ehling W, Cretteur L, Pic A, Vierstraete R, Yin Q. Development of a Laser Decoating Process for Fully Functional Al-Si Coated Press Hardened Steel Laser Welded Blank Solutions. *Proceedings of 5th International WLT-conference on Lasers in Manufacturing*. Munich, Germany; 2009, p.409-413.
- [14] Choi JK, Kim JK, Shin SM, Kim CH, Rhee SH. A study on laser welding characteristics of 1500MPa grade ultra high strength steel for automotive application. *J Korean Soc Laser Process* 2010;**13**:19-26.
- [15] Fan DW, Kim HS, Oh JK, Chin KG, De Cooman BC. Coating degradation in hot press forming. *ISIJ Int* 2010;**50**:561-568.