Laser Welding of Thin Sheet Steel with Surface Oxidation

Surface oxidation enhances the absorption of laser energy significantly and has little influence on the mechanical properties of laser welds

BY J. XIE AND A. KAR

ABSTRACT. The joining of thin sheet steel generally involves conduction mode welding, in which the reflection of the laser beam by the sheet surface is high. The absorption of laser energy by the workpiece increases significantly during keyhole laser welding, in which a vapor-plasma-filled cavity is formed. The reflectivity of cold-rolled thin sheet steel was found to be in the range of 65–80% in CO_2 laser welding. The reflectivity decreased to about 30% when the sheet surface was oxidized before laser welding. In the laser welds with surface oxidation, the oxygen inclusions and porosity were not found, but the grain size was large. However, the tensile strength of all welds — with or without surface oxidation — was higher than the base metal. The toughness of the welds with surface oxidation degraded, because of the small amount of oxygen content, but it was still comparable to the toughness of the welds without surface oxidation. The oxygen content in the welds with surface oxidation was found to be slightly higher than in the welds without surface oxidation. The mechanical properties of the welds with surface oxidation were found to improve when steel powders consisting of manganese and silicon were used during welding.

Introduction

Thin steel sheets are extensively used in industries producing products such as washer bodies, medical and electronic components. Laser welding is considered to be a suitable manufacturing process for thin sheet steel structures because of several advantages: low heat input, little distortion, small heat-affected zone (HAZ), good mechanical properties and excellent repeatability of welds. It has been reported that laser welds decreased sheet formability by 10–18%, while mash-seam welds decreased formability by 29–35% (Ref. 1). Fatigue life performance of laser welds was increased by 36–126% over resistance welds (Ref. 2). Therefore, in the future, it is expected that laser welding will be used more widely to join a variety of materials in industries.

Most thin sheet steels are cold-rolled low-carbon or mild steels. The weldability of such materials is usually excellent and lasers can be utilized to achieve good quality welds. The conduction welding mode (rather than the typical keyhole welding mode) is likely to be encountered in the laser welding of thin sheet steel (Ref. 3), when the laser beam spot size is generally comparable to the thickness of the sheet or laser intensity is insufficient to boil the materials. Conduction welding has been reported to be well suited to weld materials under approximately 0.5 mm (Ref. 3). However, a few problems in laser welding of thin sheet steel, such as the high reflection of laser beams by the sheet surface and strict requirement for workpiece fitup, limit the applications of laser welding in industries. The effect of multiple reflections of the laser beam in the keyhole, which increases the absorption of laser energy by more than 90% in keyhole welding, is not observed in conduction mode welding. A small portion of the laser energy is absorbed by the surface and the rest is reflected in laser conduction welding. This process is known as *Fresnel absorption* (Ref. 4).

A number of investigations on the reflection of laser beams by metal surfaces was carried out, but most work was for polished metals (Refs. 5–8). Theoretical values of reflectivity of polished metals were usually estimated based on Drude theory. Some theoretical and experimental data for both CO_2 and Nd:YAG lasers listed in Tables 1 and 2 show that although the reflectivity was quite high for polished metals, it decreased with an increase in temperature. It was also found that the reflectivity of AISI 4340 steels for CO_2 lasers decreased from 93.1 to 88.3% in the temperature range of 20–500°C (68–932°F) at an argon flow rate of 25 L/min (Ref. 9). Changes of reflectivity with CO_2 laser intensity for 35NCD16 steels in solid, liquid, vapor and plasma states were studied (Ref. 10). The reflectivity of polished steels decreased continuously from 95% in solid state to 85% in liquid, 70% in vapor and 60% in plasma, at a laser intensity of 10^5 W/cm^2. When the laser intensity changed from 10^5 W/cm^2 to 10^6 W/cm^2, the reflectivity of the polished steels declined from 95 to 55% in solid state, from 85 to 52% in liquid and from 70 to 45% in vapor (Ref. 10). Incident angles of the laser beam have little influence on reflectivity if the angle is less than 20 deg (Ref. 4).

Surface conditions of metals influence the reflection of laser beams signif-

KEY WORDS

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Table 1 — Experimental and Theoretical Values of Reflectivity at 10.6 μm (Ref. 7)

Metal	Measured (%)	Calculated (%)
Fe	97.7	97.1
	94.7 (500°C)	94.7 (500°C)
Ti	77.0	92.0
Zr	85.0	
Cu		98.5
Al		98.1
Mo	95.0	97.3
Ta	90.0	95.6
304 SS	90.0	90.0
	86.0 (1000°C)	86.0 (1000°C)
Ti-6Al-4V	87.0	87.0
	86.0 (400°C)	86.0 (400°C)

Table 2 — Experimental and Theoretical Values of Reflectivity at 1.06 μm

Metal	Measured (%) (Ref. 7)	Calculated (%) (Ref. 5)
Ti		61.0
V		58.0
Cr		58.0
Mn		65.0
Fe		64.0
		68.0 (1400°C)
Co		75.0
		70.0 (1400°C)
Ni		77.0
		73.0 (1400°C)
Cu	98.5	97.1
	93.3 (Liquid)	96.3 (150°C)
Al	94.4	
	78.0 (Liquid)	

Table 3 — Chemical Compositions of Filler Powders (wt-%)

	1018 Steel	Pure Iron	Manganese	Silicon
Powder 1	49.16	49.16	1.17	0.39
Powder 2	48.26	48.26	2.32	1.16

icantly, and experiments indicated surface roughening and coating could reduce the reflection of laser beams (Refs. 11–13). The surfaces of the cold-rolled sheets were smooth and the reflection of the laser beam during welding was very high, which resulted in the waste of laser energy, reduction of productivity and safety problems. It is important to understand the reflectivity of cold-rolled steel and the influence of surface treatments on the reflectivity and laser welds; however, the reflection by cold-rolled surfaces is still poorly understood and the effect of surface oxidation on the reflection of cold-rolled steel is seldom studied. The reflection of a CO_2 laser beam by the cold-rolled sheet steel and the influence of surface oxidation on the reflection were investigated in this study. As-received and oxidized steel sheets were welded using a CO_2 laser beam and the mechanical properties of the laser welds were analyzed. The effect of adding alloyed steel powders on the mechanical properties of the laser welds was also studied. These properties are reported in this article.

Experiments

The reflectivity of cold-rolled sheet steel at the wavelength of CO_2 lasers (10.6 μm) was measured by using an experimental setup as shown in Fig. 1. The CO_2 laser beam irradiated on a workpiece at an incidence angle of 15 deg, and a power detector was placed in the path of the reflected beam. The reflected laser power was measured using a power meter, and the reflectivity was determined by taking the ratio of the reflected laser power to the incident laser power.

A 400-W CO_2 laser was used for measuring the reflectivity and for welding low-carbon sheet steel. The CO_2 laser beam was focused with a ZnSe planoconvex lens with a focal length of 3.5 in. (89 mm). Both argon and helium were used as shielding gases, with a flow rate of 15 L/min. The laser power and travel speed in the measurement of reflectivity and welding were about 360 W and 0.2 mm/s, respectively. When the filler powder was used for surface-oxidized sheets, the air gap between two sheets was about 0.2 mm. The powder was pre-placed in the gap between two sheets.

The cold-rolled sheets used in the experiment were AISI 1010 low-carbon steel, with a thickness of 0.6 mm. The steel sheets were oxidized by putting them into an air furnace at 1000°C (1832°F) for 20 and 40 s, respectively. Since oxidized samples would have exhibited increased oxygen concentrations in the welds, filler powders consisting of deoxidizing elements such as manganese, silicon, titanium and zirconium were used for laser welding of the oxidized samples to improve the mechanical properties. In this experiment, manganese and silicon were added to the filler powder because of the capability of these elements to reduce the oxygen content in the weld metal. Two types of powder were designed for laser welding of oxidized steel samples, as shown in Table 3. The mesh size of the steel powder was in the range of 80–100.

The strength and ductility of the laser welds were evaluated by conducting tensile tests. To obtain the mechanical properties of such small laser welds, two notches were created at both thin sides of the welded samples (Fig. 2) to ensure the occurrence of rupture in the weld zone. Since the notched samples were not of standard size for tensile testing, the test results of the notched samples were not compared with those of standard coupons. The toughness of the laser welds was estimated by calculating the area under the stress-strain curves obtained in tensile test. The oxygen concentrations in the weld and base metals were measured by using the Auger Electron Spectroscopic (AES) technique, for which the polished surfaces of laser welds were sputtered for 10 min to remove the surface contaminants before the measurement.

Results and Discussion

Reflectivity

Reflectivity of polished metals is an optical property of the metals and it is quite high for most metals (Ref. 4). Reflectivity decreases when the temperature of the workpiece is increased and the reflectivity at melting temperature is lower than at room temperature because of the higher resistivity at the melting temperature. Reflectivity generally decreases as resistivity increases (Refs. 4, 11, 14). The temperature-dependent reflectivity for polished metals has been theoretically obtained in an earlier work (Ref. 14), as shown in Table 4. It has been found that the absorptivity of Nd:YAG lasers is about 3.16 times higher than that of CO_2 lasers and the reflectivity of polished metals for both CO_2 and Nd:YAG lasers is quite high — even at the melting temperatures. Therefore, most of the laser energy is reflected away during laser conduction welding.

The surface conditions of cold-rolled sheet metals are different from polished metals. The cold-rolled surface of metals is not as smooth as the polished surface and the presence of oil or water film on the surface can enhance the absorption of laser energy. The reflectivity of cold-rolled sheet metals is expected to be lower than that of polished metals. The reflectivity of cold-rolled sheet metals was measured for CO_2 lasers and the results are listed in Table 5. Since the reflectivity in solid and melting states is different, surface melting of various metals under the CO_2 laser irradiation of 360 W is shown in Table 5. The surface melting is usually achieved by a focused laser beam for many metals, but it is also possible for the surface to be melted by an unfocused laser beam (raw beam) for stainless steels and Inconel alloys because of their low thermal conductivity. There was a small plasma above the workpieces when surface melting occurred under the irradiation of the focused CO_2 laser beam. Table 5 shows aluminum and copper sheets have the highest reflectivities and the values for mild steels are also quite high. A lot of laser energy is lost during laser conduction welding of the cold-rolled metal sheets. The change in reflectivity with roughness for copper and aluminum is shown in Fig. 3, while the metal surface was roughened by sandpapers with various grits. Since the reflectivity is reduced by the irregular reflections of laser beams on the rough surface, the reflectivity decreases with increasing roughness.

Experimental results for the reflectivity of cold-rolled sheet steel with different surface treatments are shown in Fig. 4. The as-received sheet steel has the highest reflectivity in the range of 65–80%. For the surface-oxidized samples, the reflectivity decreases significantly — as low as 35% depending on the surface oxidation time — because of the high electrical DC (direct current) resistivity of the surface oxide films. By placing steel powders on the substrate surface, the reflectivity is found to be in the range of 20–35%, because of the irregular reflections of the laser beam by the steel powders.

In the laser conduction welding of thin sheet steel, strong reflection of the CO_2 laser beam results in the waste of laser energy and safety problems. The oxidized samples reduce the reflection of the laser energy; however, it is necessary to understand the influence of the surface oxides on the mechanical properties of the laser welds. As-received, surface-oxidized and powder preplaced samples were welded by using CO_2 lasers. The mechanical properties of these welds are compared in the following section.

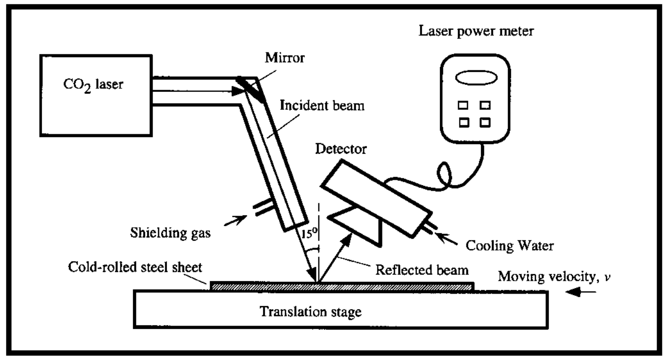

Fig. 1 — An experimental setup for measuring reflectivity.

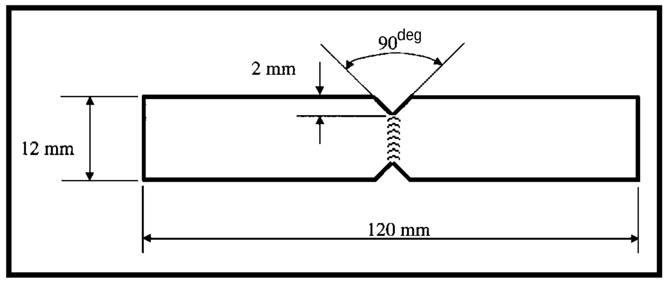

Fig. 2 — A notched specimen for tensile tests.

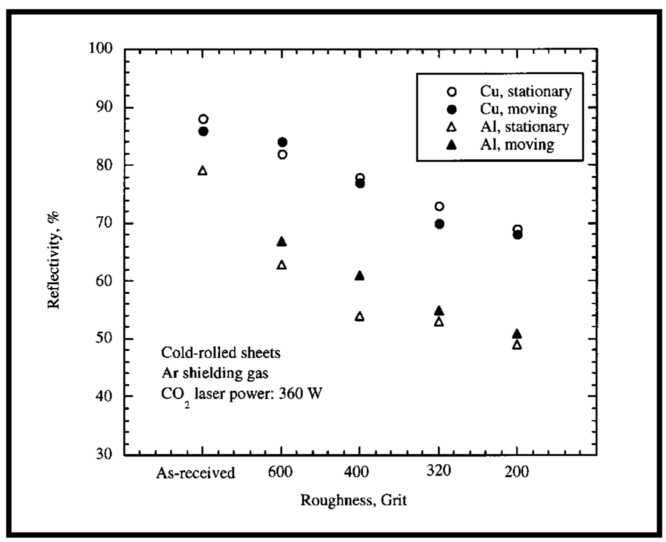

Fig. 3 — Effect of surface roughness on reflectivity for copper and aluminum.

Laser Weld

Laser welds with surface oxidation were cross sectioned to analyze the defects in the welds. No oxide inclusions and porosity were found in the weld metal, but the grain size was quite large, as shown in Fig. 5. It seems that the oxide film decomposes during laser irradiation and a small amount of oxygen is dissolved in the weld metal. The iron oxide decomposes into iron and oxygen, with most of the oxygen being carried away by the shielding gas. Only a small amount of the oxygen is retained in the weld pool because of the low solubility of oxygen in liquid iron (Ref. 15). The small amount of oxygen presented in the weld metal is probably due to the low welding speed used in the welding experiments of this study. The low welding speed provides sufficient time for the oxide film to decompose completely, which may be the reason for the absence of oxide inclusions and porosity in the welds. The relative oxygen atomic concentrations in the base metal and welds that were determined by Auger Electron Spectroscopy (AES) are shown in Fig. 6. There is little oxygen content in the base metal and the value of the oxygen con-

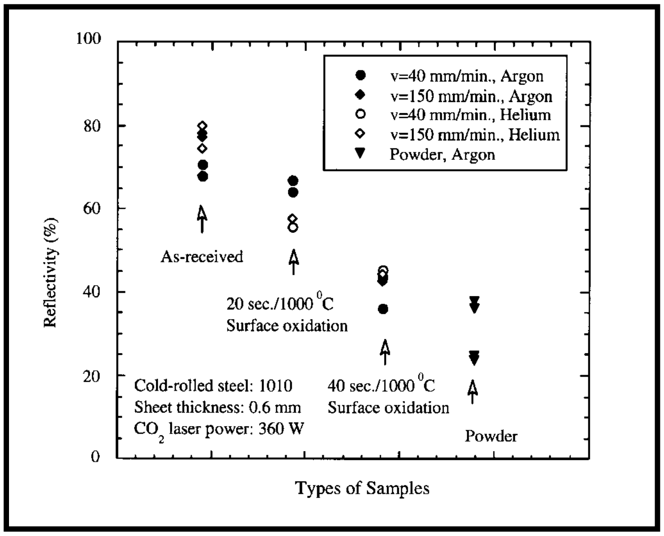

Fig. 4 — Reflectivity of cold-rolled sheet steel with various surface conditions.

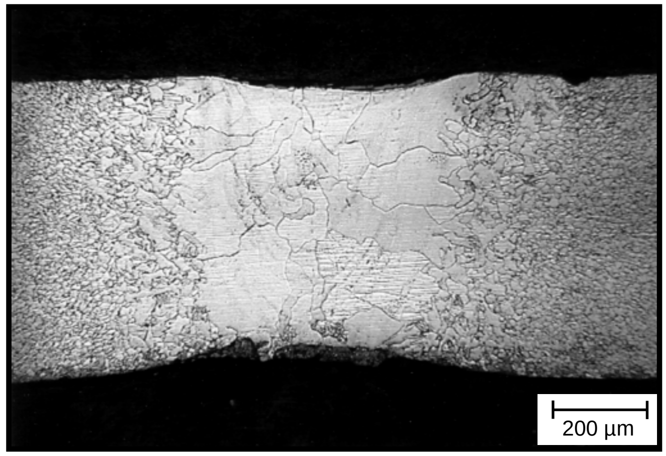

Fig. 5 — A laser weld made with surface oxidation.

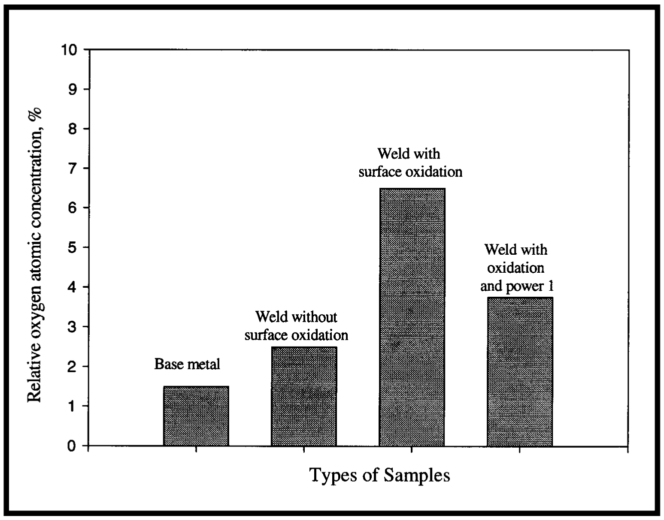

Fig. 6 — Oxygen content in laser welds.

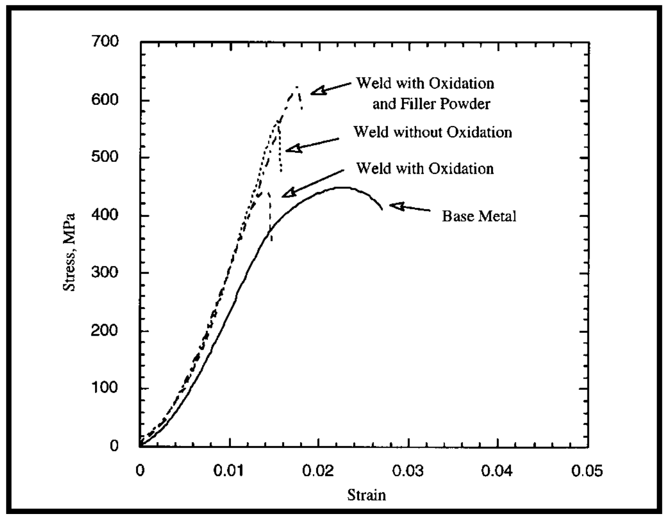

Fig. 7 — Typical stress-strain curves obtained in tensile tests.

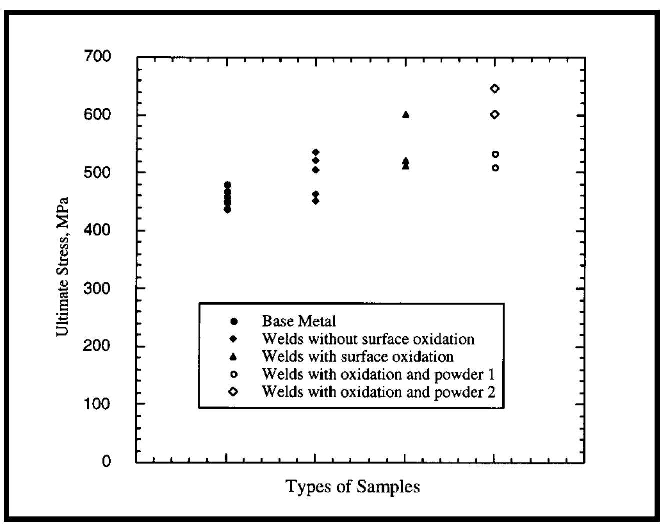

Fig. 8 — Ultimate tensile strength of laser welds and base metal.

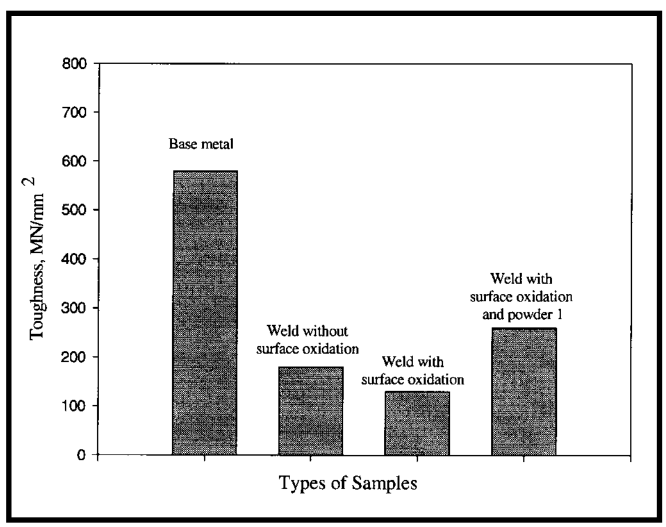

Fig. 9 — Toughness of laser welds and base metal.

Table 4 — Reflectivity of Polished Metals at the Room and Melting Temperatures (%) (Ref. 14)

	Room Temperature			Melting Temperature (Liquid Phase)		
	CO_2	COIL[(a)]	Nd:YAG	CO_2	COIL[(a)]	Nd:YAG
Wavelength (μm)	10.6	1.315	1.06	10.6	1.315	1.06
Aluminum	98.1	94.7	94.1	93.6	81.8	79.8
Copper	98.5	93.6	95.1	94.9	85.5	83.9
Iron	96.9	91.3	90.3	87.0	63.1	58.9
Nickel	95.3	86.6	85.1	89.7	70.8	67.4
Titanium	91.9	76.9	74.3	86.3[(b)]	61.1[(b)]	56.7[(b)]
Carbon Steel	97.3	92.2	91.3	87.9	65.9	61.8
Stainless Steel	90.3	82.4	69.3	86.0[(b)]	60.3[(b)]	55.8[(b)]

(a)Chemical Oxygen-Iodine Laser.
(b)Values at the temperature just below melting point.

centration in Fig. 6 is background noise from the AES instrument. The oxygen concentration is slightly higher in the weld with surface oxidation than without oxidation. The addition of steel powder to the weld zone during welding decreases the oxygen concentration in the weld because of the presence of deoxidizing elements Mn and Si in the steel powder.

Typical stress-strain curves obtained in tensile tests are shown in Fig. 7. The base metal has the highest elongation of all the welds (Fig. 7), but its ultimate strength is lower than all the welds — Fig. 8. The tensile strength of the welds with surface oxidation is slightly higher than those without oxidation, possibly because the dissolved oxygen atoms in the welds act as solutes in the metal matrix, deforming the metal lattices, and the deformed lattices enhance the strength of the weld metals. This hardening mechanism is similar to the solid-solution hardening. When steel powders are added during welding, the oxygen content in the welds decreases because of chemical reactions between the deoxidizing elements and iron oxide; therefore, the hardening effect of the oxygen atoms becomes insignificant. As a result, the strength of the samples welded by powder 1 (with less Mn and Si than powder 2) is close to the strength of the samples without surface oxidation and is slightly lower than the samples with surface oxidation. When powder 2 (with more deoxidizing elements than powder 1) is used, the strength of the weld is enhanced by the alloying elements, Mn and Si, instead of the oxygen atoms.

The toughness of the welds is approximated by calculating the area under the stress-strain curves obtained in tensile tests and is presented in Fig. 9, which shows that the base metal has the highest toughness. It is notable that the toughness of the weld with surface oxidation is only slightly lower than the weld without oxidation. The toughness of the welds improves with the addition of alloying powder.

Table 5 — Reflectivity of As-Received Cold-Rolled Sheet Metals for CO_2 Lasers

Materials	Reflectivity (%)	Surface Melting	Focused Beam
Aluminum	79–90	Yes	Yes
Copper	80–92	No	Yes
Mild Steel	65–80	Yes	Yes
Stainless Steel (304)	~33	Yes	No
Titanium	46–50	Yes	Yes
Inconel	44–64	No	No
Inconel	36–51	Yes	Yes

In general, surface oxidation decreases the reflection of laser beams and introduces a small amount of oxygen atoms into the welds. The tensile strength of the weld with surface oxidation is good and the toughness is acceptable. These results indicate that surface oxidation is a possible means of reducing the reflection of laser beams without sacrificing the mechanical properties of the welds.

However, oxidizing the surface of the workpiece before welding is difficult for certain industrial applications. Surface oxidation could be achieved by adding reactive gases in the shielding gas. It was reported that mixed shielding gas, with an added 10% oxygen in argon, could increase the weld depth significantly (Ref. 16), and the CO_2 gas could be used as a shielding gas (Ref. 17). In addition, the results obtained from the study imply that little or no shielding gases may be used for welding low-carbon steel because acceptable laser welds can be produced in an active shielding environment. If these results are verified by further studies, substantial manufacturing costs can be saved in production.

Conclusions

1) The reflectivity of as-received cold-rolled sheet steel is in the range of 65–80% in CO_2 laser conduction welding. Surface oxidation could reduce the reflectivity to approximately 30%.

2) In laser welds with surface oxidation, oxygen inclusions and porosity are not present, but the grain size is large. The oxygen concentration in the welds with surface oxidation is slightly higher than in the welds without surface oxidation.

3) The tensile strength of the welds is higher than that of the base metal. The toughness of the welds with surface oxidation is slightly degraded, because of the slight presence of oxygen in the weld; however, it is still comparable to the toughness of welds without surface oxidation.

4) The addition of alloyed steel powders containing silicon and manganese can improve the mechanical properties and reduce the oxygen content in the welds.

Acknowledgment

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