Gas-Assisted Laser-Metal Drilling: Experimental Results

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An experimental investigation was conducted to clarify the role of an assist gas during gas-assisted laser-metal drilling for incident laser fluxes on the order of 10^6 W/cm^2. In particular, the effect of change in absorptivity and other thermophysical properties associated with metal oxide formation on laser drilling time was investigated. A 100-W, average power, pulsed Nd-YAG laser was used to drill holes in Al6061, Cu, 304 stainless steel, and low C steel. A coaxial nozzle was used to supply an assist gas during the drilling process. The minimum pulse width (drilling time) required to drill a hole through a given thickness of metal sample using argon and oxygen assist gas was determined. The results showed that the oxide formed during laser drilling with oxygen affected the drilling time two ways: 1) by changing the absorptivity of the surface and 2) by changing the temperature required to expel the molten material (due to the difference in melting point of the metal and metal oxide). It was concluded that these two competing effects determine whether an oxygen assist gas jet is helpful in low-power drilling of metals.

Introduction

DURING the early 1960s the range of drilling applications for available lasers was very narrow, with the perforation of baby bottle nipples by a CO_2 laser beam one of them. Another of the early industrial applications that emerged was piercing diamonds. Diamonds were drilled to precise diameters, for the production of dies, ranging from under 0.025 mm to over 1.25 mm and with depths to 12.5 mm. This application (believed to be the first industrial use of lasers) was developed by Western Electric Company in 1962 and put into production in 1964.[1] Today, the aerospace and automobile industries use lasers for production of large-volume holes for cooling and lubrication purposes in engine components. Laser hole drilling is also used to produce tiny orifices for nozzles, apertures for electron beam instruments, and pinholes for optical work. Clearly, laser drilling has an important role to play in the developing areas of modern materials processing and manufacturing. Therefore, it is vital to understand the fundamental thermophysical processes that govern laser-metal interaction and laser drilling.

A variety of physical and chemical processes can take place during laser-metal interaction including melting, vaporization, surface oxidation, and molten material expulsion. Two of these processes, vaporization and molten material expulsion, result in removal of sample material, i.e., drilling. The material removal mechanism and rate depend on the incident laser power level, the thermal properties of the metal, and whether or not an assist gas jet is used. Generally, the response of a metal target to laser heating (without assist gas jet) can be described as follows. The target absorbs laser energy in a thin surface region. This energy is conducted axially and radially into the surrounding colder metal. If the absorption rate is low enough ($<10^5$ W/cm^2) compared to the rate of conduction, the target surface will remain below the melting point. At higher absorption rates, the surface region of the metal will melt and perhaps begin to vaporize (this discussion temporarily ignores oxidative effects). If the rate of vaporization is great enough, the recoil pressure force generated will cause ejection of metal in the molten state. At still higher absorption rates ($>10^7$ W/cm^2), vaporization becomes the dominant mechanism of material removal from the target.

In most drilling applications an assist gas jet is used coaxially with the laser beam to protect optics and facilitate material removal. At low incident powers, the assist gas jet enhances molten material removal due to the shearing action of the gas acting on the molten material (referred to as melting-flushing or melting-blowing). The melting-blowing method reduces the power required for drilling compared with the situation when no gas jet is used. At high powers, where vaporization dominates material removal, the assist gas jet enhances drilling by removing absorptive vapors and debris that can prevent the incident energy from reaching the target. It has been noted that holes drilled with high-power lasers (more removal of metal by vaporization) seem to have better quality (better hole diameter control and straightness of hole) than holes drilled by gas jet assisted low-power lasers (more removal of material in molten state). In contrast to high-power drilled holes, low-power laser-drilled holes tend to have diameters larger than the laser beam size, a significant amount of taper, and melt deposits along the sides of the hole. But for purposes where the hole geometry is not so important (e.g., holes drilled for cooling or lubrication purposes), the use of an assist gas with low laser power represents an efficient way to drill a functional hole.

A survey of the literature indicates that some aspects of the laser-metal drilling process are relatively well-understood, such as the influence of incident power, focal plane position, number of pulses required to drill a hole for a given thickness of material, etc. A condensed summary of the work done in these areas can be found in Refs. 1–4. However, only a few publications in the open literature discuss the use of an assist gas jet during laser drilling (in contrast to the extensive body of literature on gas-assisted laser cutting). Among those who have studied gas jet effects in laser drilling, Tiffany[5] states that the main function of the gas nozzle in laser drilling is to protect the focusing lens from debris and that the gas stream appears to have little, if any, effect on the drilling process. Ruselowski[6] observes that oxygen produces the best hole in iron, nickel, and their alloys because it helps burn the metal away. Ruselowski also recommends the use of air for metals such as aluminum and states that care should be taken while drilling titanium, since Ti burns very easily with gases such as O_2 and N_2. Heglin[7] also observes that the use of compressed air or oxygen increases the metal removal rate in some materials due to exothermic reaction. From these studies it seems that the general opinion at present is that an oxygen jet

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generally helps the drilling process, since it seems to help the cutting process, due to exothermic reaction. However, no systematic study has yet been done to understand the role of an assist gas in laser drilling.

One question, in particular, that has not been resolved is what role surface oxidation plays in influencing the laser drilling process. It has been observed that the formation of an oxide layer generally increases the absorptivity of the target.[8,9] Therefore, an oxygen jet would be thought to enhance the drilling process. However, if the melting point of the oxide formed is significantly higher than that of the metal, the formation of a solid oxide layer will impede the flow of the liquid metal. Consequently, a larger heating time may be required to raise the metal surface to the oxide melting point so that the molten material can be expelled by the gas flow.

The primary objective of the experimental study described here was to investigate the role of an assist gas during single-shot Nd-YAG laser drilling of different metals. In particular, the effects associated with the metal oxide formation on drilling time were investigated. The role of oxygen assist was characterized based on two factors: 1) the change in the absorptivity of the surface due to oxide formation and 2) the change in the temperature required to expel the molten material caused by the difference in melting points of oxide and metal. The effects of metal thickness, incident laser power, and assist gas pressure on drilling time were also investigated.

Experimental Setup

A parametric study of the laser drilling of four different metals (Al6061, Cu, 304 stainless steel, and low C steel) was conducted. Two different assist gas jets were used: oxygen and argon. A schematic diagram of the experimental setup used is shown in Fig. 1a. A 100-W average power multimode Nd-YAG pulsed laser (model MS 810, J. K. Lasers, Inc.) with a "top hat" spatial profile (5% intensity variation across the top) was used throughout the study. The laser was triggered by an externally supplied voltage signal that controlled the power output, shape, and width of a laser pulse. Three different laser pulses, P_1, P_2, and P_3, were used in the study as shown in Fig. 1b. The average power for these pulses was estimated by dividing the known value of energy (Joules) per pulse, read from the laser front panel meter, by the pulse width. The average powers for P_1, P_2, and P_3 were 550, 1300, and 2250 W, respectively. The focal plane of the focusing lens was kept at the surface of the sample. The focal length of the focusing lens was 80 mm, and the nozzle exit plane diameter was 1 mm. The gas pressure was monitored at the gas bottle exit. A 10-ft-(3.05-m-) long, ¼-in.- (0.635-cm-) diam rubber hose was used to connect the gas bottle to the nozzle. The samples were drilled in their as-received conditions. However, acetone was used to remove the grease from the samples before drilling. The minimum time required to drill a hole through a given thickness of sample was obtained for both argon and oxygen with similar optical conditions, gas pressure, and incident laser power. The minimum time was defined as the lowest value of pulse width in milliseconds required to drill a hole through a given sample. Penetration was checked by holding the sample against the room light, and the hole was declared a through hole if light was observed through the hole. A typical hole geometry is sketched in Fig. 1c, and average hole sizes for the various samples are given in Table 1.

Results and Discussion

Assist Gas Dependence

Figure 2 shows the time taken to drill through 1/32-in.- (0.794-mm-) thick Al6061, Cu, 304 stainless steel, and low C steel samples [low C steel sample was 1/16-in.- (1.588-mm-) thick] for an incident laser power of 1300 W (P_2) with an assist gas pressure of 40 psig (275.88 kPag). It can be seen that for the Al6061 sample the drilling time with oxygen assist (0.68 ms) is longer than that with argon assist (0.56 ms). However, for the Cu sample the drilling time with oxygen assist (2.2 ms) is smaller than that for argon assist (3.1 ms). For the 304 stainless steel sample there is no difference in drilling time between oxygen and argon assist case (0.68 ms). For the 1/16-in.- (1.588-mm-) thick low C steel sample the drilling time for oxygen assist (4.8 ms) is slightly smaller than that for argon assist (5.0 ms).

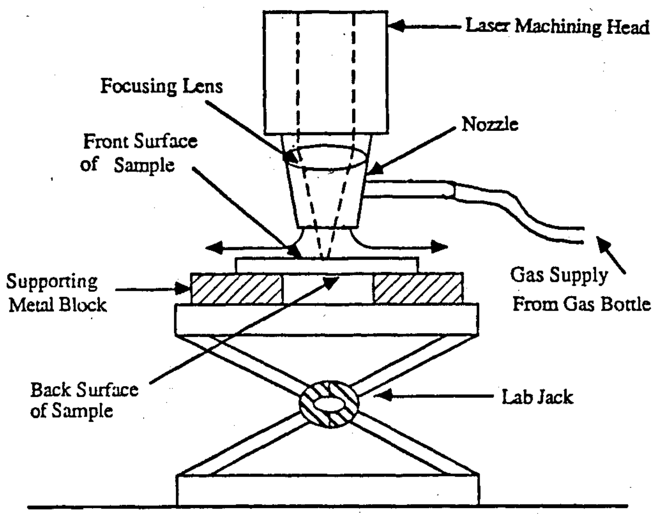

Fig. 1a Schematic diagram of experiment.

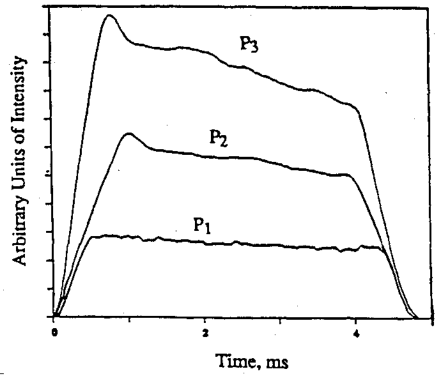

Fig. 1b Temporal profiles of laser pulses; P_1 (550 W), P_2 (1300 W), and P_3 (2250 W).

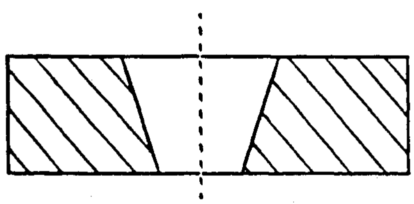

Fig. 1c Typical laser drilled hole geometry.

An explanation for the results of Fig. 2 is as follows. The laser irradiation heats a spot on the surface of the metal, causing its temperature to increase and eventually reach the melting point. Once a molten pool is formed at the target surface, the assist gas jet removes the molten material from the interaction zone and a melting front penetrates into the unmelted region of the sample to continue the drilling process. If the assist gas contains oxygen, surface oxidation, which takes place during the early heating period, changes (usually increases) the absorptivity of the surface, as reported by the authors elsewhere.[9] Table 2 lists the values of the room temperature and maximum possible oxidation-enhanced absorptivities for metallic samples reported elsewhere by the authors.[9] If the oxide formed during this period has a substantially higher melt-

Table 1 Typical sizes of laser drilled through holes at minimum drill time

Metal	Radius, μ (± 25)
Al6061	200
Cu	100
304 Stainless steel	150
Low C steel	250

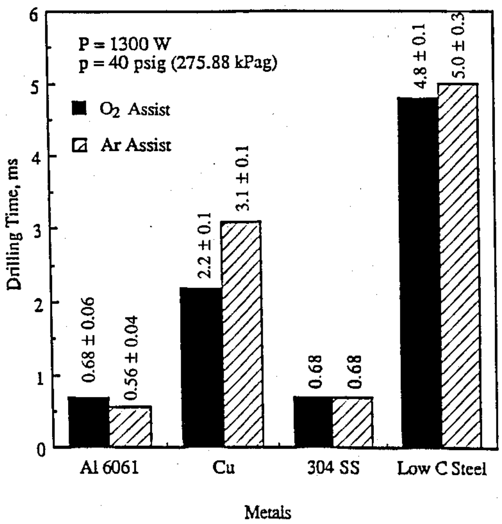

Fig. 2 Drilling time for P_2 (1300 W) with sample thickness of 1/32 in. (0.794 mm), except low C steel, 1/16 in. (1.59 mm).

ing point than that of the metal, the surface temperature required to melt the oxide and expel the molten material will be significantly increased. Thus, the potentially important factors associated with the oxide formation that can affect the drilling time, under the conditions of present study, are the change in the absoptivity of the surface and the difference in the melting points of the oxide and metal. The competing effect of these two factors determines whether the oxygen assist is helpful to the drilling process.

Based on the preceding hypothesis, it would seem that, under the conditions of the present study, the reason it takes longer to drill a hole in Al6061 when oxygen is used as an assist gas rather than argon is that the increase in absorptivity is relatively small (a factor of about 1.5, from 0.28 to 0.4 as listed in Table 2) due to oxidation for Al6061, but the melting temperature T_m of aluminum/magnesium oxide formed (Al6061 contains 1% of Mg) is 2.5–3 times larger than that of Al ($T_{m,\,Al_2O_3} = 2345$ K, $T_{m,\,MgO} = 3125$ K, and $T_{m,\,Al} = 933$ K). Therefore, a small gain in absorptivity due to oxide formation is offset by the higher melting temperature of the oxide, which requires the sample to be heated longer before the molten expulsion takes place and drilling proceeds.

In the case of Cu it takes less time to drill a hole when oxygen is used as an assist gas compared to when argon is used. The mixture of Cu oxides formed during oxidation of Cu increases the absorptivity of the surface significantly (by a factor of 10, from 0.02 to 0.2 as listed in Table 2), and at the same time the corresponding difference between the melting temperature of oxide and metal is small ($T_{m,\,Cu_2O} = 1508$ K, $T_{m,CuO} = 1599$ K, and $T_{m,\,Cu} = 1356$ K). Therefore, in the case of Cu, oxide formation proves to be advantageous in terms of reducing the drilling time. In the case of 304 stainless steel it was seen in an earlier work[9] that due to its relatively high value of intrinsic metal absorptivity and inherent oxidation resistance, 304 stainless steel is barely affected in terms of its absorptivity by the type of gas environment. Furthermore, 304 stainless steel has a relatively low thermal conductivity; therefore, the heating rate is insensitive to gas environment. Thus, there should be very little difference in drilling time between oxygen and ar-

Table 2 Absorptivities of metallic samples[9]

Metal	Room temp. value	Oxidation-enhanced value
Al6061	0.28	0.4
Cu	0.02	0.2
304 Stainless steel	0.32	0.32
Low C steel	0.45	0.6[a]

[a] From Ref. 11.

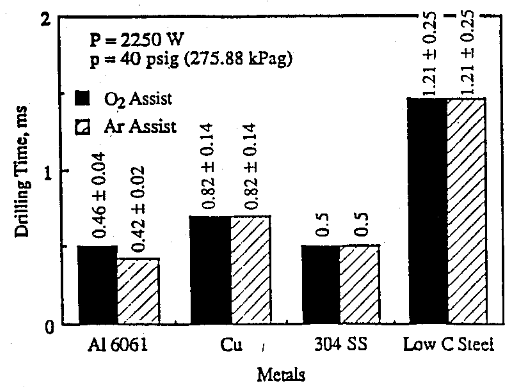

Fig. 3 Drilling time for P_3 (2250 W) with sample thickness of 1/32 in. (0.794 mm), except low C steel, 1/16 in. (1.59 mm).

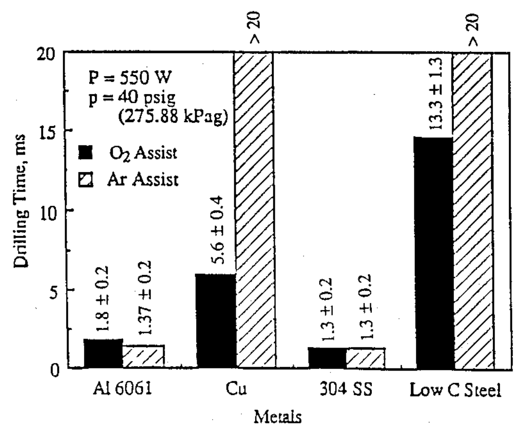

Fig. 4 Drilling time for P_1 (550 W) with sample thickness of 1/32 in. (0.794 mm), except low C steel, 1/16 in. (1.59 mm).

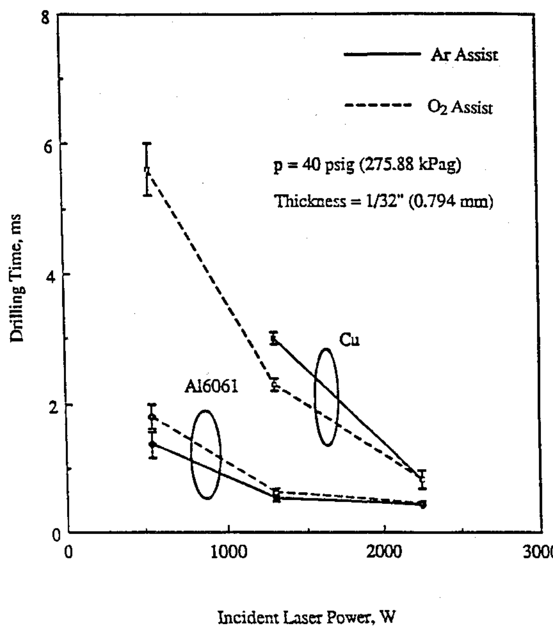

Fig. 5 Drilling time for Al6061 and Cu (effect of incident power and assist gas).

gon, which indeed is the case, as can be seen in Fig. 2. In the authors' earlier work[9] the gas environment was also observed to have a negligible effect on the absorptivity of low C steel. Figure 2, however, shows a small difference in drilling time [0.2 ms out of 5.0 ms for a 1/16-in.- (1.588-mm-) thick sample] between oxygen and argon for low C steel. This is not very surprising because a small amount of enhancement due to oxide formation seems likely for non-oxidation-resistant low C steel. The slightly lower value of drilling time for oxygen may be due to the fact that the iron oxides are slightly more absorptive than iron (the normal spectral absorptivity of iron oxide being about 0.6, or 1.5 times that of iron, at 1.06 μm, as reported in Refs. 10 and 11), and the difference in melting points of iron oxide and iron is small ($T_{m,\,FeO} = 1642$ K, $T_{m,\,Fe_2O_3} = 1840$ K, and $T_{m,\,Fe} = 1808$ K).

Power Dependence

It is also interesting to note the effect of incident power by comparing Figs. 2–4. As the input laser power increases ($P_3 = 2250$ W, Fig. 3), the difference in drilling time between oxygen and argon becomes negligible or reduces to zero, and as the incident laser power decreases ($P_1 = 550$ W, Fig. 3b), the difference in drilling time between oxygen and argon increases. This is because at higher incident powers the heating rate is increased and the time available for the formation of oxide is reduced. Thus, the oxide-related effects do not play an important role at higher heating rates. In the extreme case, at very high-incident laser fluxes (10^9W/cm^2 and above), the assist gas would have very little effect on the process because the heating rate would be so high that most of the material would leave the surface in vapor form. In the other extreme, if the incident laser flux is very low, leading to very slow heating rate, there would be sufficient time available for oxide formation, and the effects associated with oxide formation would be more prominent.

It should be pointed out that incident laser fluxes of the order of 10^6W/cm^2 are capable of vaporizing certain metallic target surfaces and, therefore, some material does get removed in the vapor form during the drilling process. But as long as the material removed in the vapor form is small compared to the material removed in the molten state, the previously discussed phenomena related to oxide formation will be still observed.

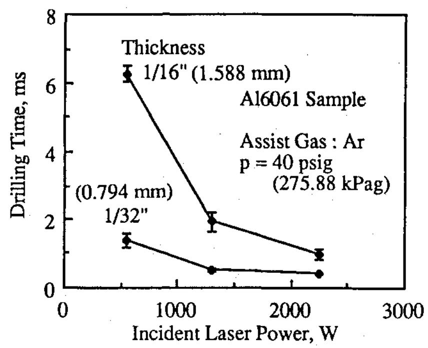

Fig. 6 Drilling time vs incident laser power for Al6061 (thickness dependence).

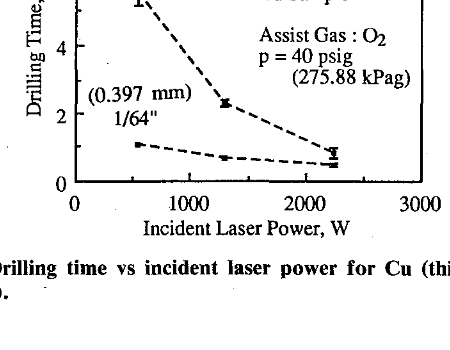

Fig. 7 Drilling time vs incident laser power for Cu (thickness dependence).

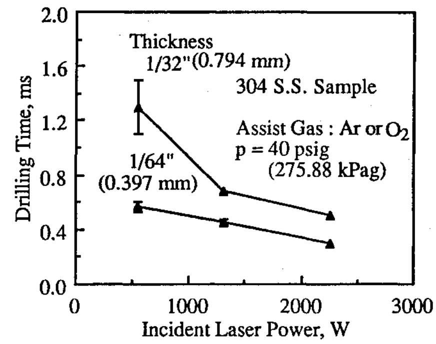

Fig. 8 Drilling time vs incident laser power for 304 stainless steel (thickness dependence).

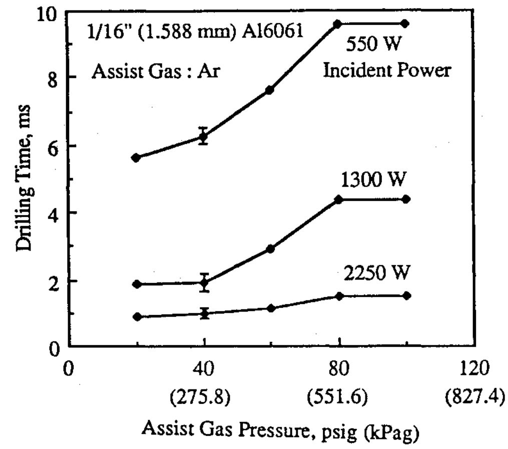

Fig. 9 Drilling time vs gas pressure for Al6061 sample.

The dependence of drilling time on incident laser power for a given metal and assist gas is shown in Fig. 5. It can be seen in Fig. 5 that, as the incident laser power increases for a given thickness of metal and assist gas, the time required to drill a hole through a sample decreases. At higher-incident power levels, the heating rate increases and the melting front moves into the solid region with a higher velocity. At very high-incident levels, the amount of material removed by vaporization will increase and the recoil pressure forces generated will also help the assist gas to increase the molten metal expulsion. All of the aforementioned effects reduce the drilling time. For a given incident laser power, it can be seen in Fig. 5 that drilling times for the copper are high compared to those for the Al6061. The lower room temperature absorptivity and higher thermal conductivity of the copper compared to Al6061 are responsibile for the observed effect.

Thickness Dependence

Since argon was found to be helpful in reducing the drilling time for Al6061 and oxygen for Cu, further parametric studies concentrated on the use of argon for drilling Al6061 and oxygen for drilling copper. The results of drilling time vs incident power for different sample thickness are plotted in Figs. 6 and 7 for Al6061 and Cu. At a given incident power level, as the sample thickness increases, the drilling time increases. For a given incident laser power, as the thickness increases, the time taken by the melting front to reach the bottom of the sample will increase, which increases the drilling time. It is also interesting to note (Figs. 6 and 7) that the drilling time decreases linearly with decreasing thickness for Al6061 and Cu at high-incident powers, whereas at low powers the drilling time

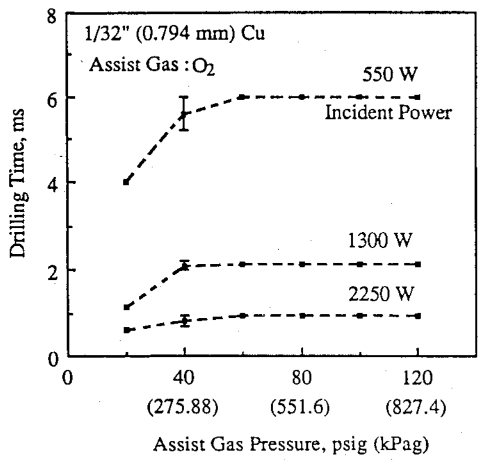

Fig. 10 Drilling time vs gas pressure for Cu sample.

decreases much more rapidly. There are two possible reasons for this behavior: 1) radial conduction losses are more pronounced at low powers than at high powers, and 2) at lower-incident laser power, more material gets removed in the molten state (i.e., material removal depends on the assist gas expulsion). As the hole depth increases, it is more difficult for molten material to escape from the bottom of the hole, which results in a higher drilling time. However, at higher-incident laser power, most of the material is removed in the vapor form; hence, the role of an assist gas in the material removal process becomes less significant. Therefore, at higher-incident laser power (above 2250 W), as the sample thickness is doubled, the drilling time also doubles. Similar results were obtained for 304 stainless steel and are plotted in Fig. 8.

Pressure Dependence

Results of drilling time dependence on assist gas pressure, as measured at the gas bottle exit, are plotted in Figs. 9 and 10. At all incident power levels and for both argon and oxygen assist cases, it is observed that as the assist gas pressure increases, the drilling time increases up to a certain pressure, beyond which the drilling time remains constant for further increase in the pressure. At first this seems contradictory to intuition, which would indicate that as the assist gas pressure increases, the gas flow should be able to remove more molten metal from the laser-metal interaction zone and the drilling time should decrease. However, other phenomena associated with the pressure increase, as discussed in the following paragraph, explain the apparent contradiction.

In their study of gas-assisted laser cutting of stainless steel, Kamalu and Steen[12] observed that at high pressures the formation of a density gradient field changes the refractive index of the medium between the workpiece and the gas nozzle, which defocuses the laser beam. Schlieren pictures of a nozzle and workpiece at high gas flow rates were taken, and formation of a density gradient field was observed. The formation of a density gradient field tends to reduce the flux density at the surface of the sample by increasing the focused beam radius. The reduction in flux density will translate into an increase in minimum drilling time required to drill a hole through a given metal sample. Since the main objective of this study was to investigate the oxide formation effect in more detail, further efforts to investigate the mechanism responsible for the observed pressure dependence were not made.

Nonstoichiometric Oxide Layer Effect

It was mentioned earlier that an increase in absorptivity by a factor of 1.43 (from 0.28 to 0.4) was expected for Al6061 due to aluminum/magnesium oxide formation. This magnitude of increase might seem surprisingly high, given that the absorptivities of solid aluminum and magnesium oxide are essentially no larger than that of Al6061. However, it should be noted that the absorptivity of a thin, nonstoichiometric mixture of aluminum and magnesium oxide or aluminum and aluminum oxide near the surface is much greater than that of the metal alloy Al6061 or either solid oxide in pure form. The formation of a dark magnesium oxide during oxidation of Al/3% Mg alloy has been reported by Smeltzer.[13] Furthermore the absorptivity of aluminum oxide typically increases significantly upon melting.[14] The effect of a nonstoichiometric oxide layer on surface absorption was further investigated by drilling 1-mm-thick alumina samples using argon and oxygen gas assist. Based on a previous study,[15] which showed a significant difference in alumina absorptivity between oxidizing and nonoxidizing atmosphere, it was postulated that in argon a nonstoichiometric, highly absorbing surface layer might be formed that would give lower drilling times. However, it was observed that for incident powers of 550 and 2250 W the time taken to drill a hole was the same for both argon and oxygen (1.4 and 0.6 ms, respectively). This was taken as evidence that a highly absorbing nonstoichiometric surface layer did not form under these conditions of rapid laser heating of Al_2O_3. These observations were also consistent with the results of Longfellow,[16] who observed no notable changes in drilling characteristics between air, nitrogen, argon, and oxygen jets during drilling of alumina samples using a CO_2 laser.

Conclusions

Experimental investigation performed in this study clarified the role of an assist gas during laser-metal interaction for incident laser fluxes on the order of 10^6 W/cm^2. The important factors associated with the oxide formation that affect the laser energy absorption and material removal rate during oxygen-assisted laser-metal drilling were observed to be the change in the absorptivity of the surface and the change in temperature required to expel the molten material (because of the difference in the melting point of metal and oxide).

The results showed that the choice of an assist gas during laser drilling of metals affected the drilling time. For an incident power of 1300 W and assist gas pressure of 40 psig (275.88 kPag), it was seen for Al6061 that the drilling time with oxygen assist was higher than that with argon assist. For Cu the trend was reversed, and the drilling time with oxygen assist was lower than that with argon assist. The assist gas had no effect on the drilling time for 304 stainless steel. Low C steel behaved similar to Cu. It was concluded that the oxide layer formed during the oxygen-assisted laser drilling process was affecting the drilling time in two ways. One effect was the changing of the surface absorptivity due to oxide formation, and the other was the change in the temperature required to expel the molten material because of the difference in the melting point of metal and oxide. The competing effect of these two phenomena determined whether oxygen assist decreased or increased the drilling time. It was also observed that for higher-incident laser power level (2250 W) the difference between oxygen and argon assist vanishes, probably because of the higher heating rates associated with the higher-incident laser power. On the other hand, for lower-incident laser power level (550 W) the difference between oxygen and argon assist increases, probably because of lower heating rates, which allows more time for oxide formation. Therefore, as the laser power increases, the role of an assist gas becomes more physical in nature and probably is limited to molten material removal only.

It was observed that drilling time increases as sample thickness increases and decreases as the incident laser power increases. It was also observed that as the assist gas pressure increases the drilling time increases for Al6061 and Cu until a critical value of pressure is reached. Beyond this critical pressure, the drilling time is independent of the gas pressure. The reason for the observed pressure dependence could be the formation of a density gradient field in front of the target surface, which defocuses the laser beam. Thus, for low-power gas-assisted laser-metal drilling, the role of an assist gas extends beyond the traditional roles of optics protection and molten material removal.

Acknowledgment

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