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Material processing with pulsed radially and azimuthally polarized laser radiation

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ABSTRACT We report on the generation of radially and azimuthally polarized Q-switched laser radiation and its application in material processing. The power levels were sufficiently high to study micro-hole drilling in different metals. Depending on the optical properties of the metal, either radial or azimuthal polarization shows the best efficiency and the effect is attributed to waveguiding. For steel, a comparison to linearly or circularly polarized laser radiation indicates that the doughnut-shaped beam with azimuthal polarization is the most energy-efficient in producing holes of the same diameter and depth.

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1 Introduction

Generating radially polarized laser light has gained considerable attention as theoretical arguments predict it to be the ideal state of polarization for a variety of applications such as cutting of metals [1], accelerating electrons in a longitudinal configuration [2], optical lithography [3], or 3D trapping of metallic Raleigh particles [4]. In general, two different routes have been pursued to obtain radially or azimuthally polarized radiation. In the extra-cavity approach, the laser output is manipulated through a combination of suitable optical elements [3, 5]. In the intra-cavity approach, which has also been utilized in this work, the laser resonator itself is modified in a way that the transverse mode exhibits the desired radial profile [6–13].

In a recent theoretical study [1] laser cutting efficiencies of various modes of polarization were compared with all other beam parameters remaining unchanged. The authors concluded that the use of radially polarized light increases the cutting depth and/or the cutting speed by a factor of between 1.5 and 2 compared to the commonly used circularly polarized light. The reason being that radially polarized light is globally of the p-type with respect to the cutting surface. That is, the absorption is always maximal and possesses cylindrical symmetry, assuring an efficient energy transfer to the material and forestalling an early collapse of the drilling channel as it is observed for linearly polarized light.

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However, to the best of our knowledge, no experimental results have been published investigating the laser–material interaction with radially or azimuthally polarized beams at intensities well above the melting or the ablation threshold. Here, we start by analyzing micro-hole drilling in metals utilizing Q-switched radially and azimuthally polarized infrared laser radiation. We do this for two reasons: first, drilling requires less energy than cutting and, second, it is easier to quantify and to compare drilling efficiencies for various modes of polarization. Nevertheless, we anticipate that the results have some repercussion also for cutting. Our paper is organized as follows: we first describe the experimental setup, starting with the laser, which produces Q-switched and radially polarized radiation. The next section begins with a simple and intuitive model based on the arguments in [1] and experimental results to test this model. As expected from earlier literature [14–19], the comparison reveals significant discrepancies, which may be resolved by a more sophisticated, but yet still qualitative, model. The paper ends with a comparison to standard types of polarization, namely linear and circular polarization.

2 Experimental setup

To generate radially polarized light we have modified a commercial Nd:YAG laser resonator, exploiting the thermally induced birefringence in the laser rod [10, 11, 20]. The geometry of the setup is shown in Fig. 1. In addition to the standard elements, a negative focal length lens and a plane acousto-optic modulator at normal incidence have been inserted into the resonator. The lens together with the thermally induced birefringence in the laser rod creates a stability regime that strongly favors the radial polarization. It is important to use a plane Q-switch at normal incidence to preserve the state of polarization.

The Q-switched laser was operating at a wavelength of 1064 nm with a pulse duration between 80 and 120 ns, depending on the pump power. The repetition rate was 1560 Hz and the maximum power about 4.6 W. The near-field intensity profile resembled a characteristic doughnut shape as seen in Fig. 2a. The M^2 values of 2.2 ± 0.1 and 2.3 ± 0.1 for radial and azimuthal polarization deduced from the z-scan measurements shown in Fig. 2b were close to the theoretical limit of 2.3 [21]. In order to verify that the laser radiation was radially polarized, the transverse mode profile was measured after

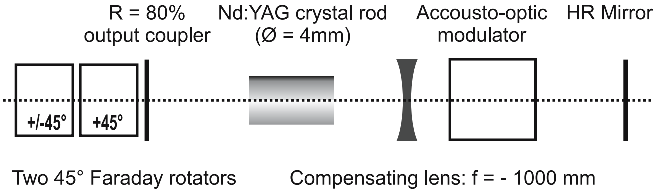

FIGURE 1 Laser resonator setup with compensation lens. The two Faraday rotators are used to convert the radial to azimuthal polarization

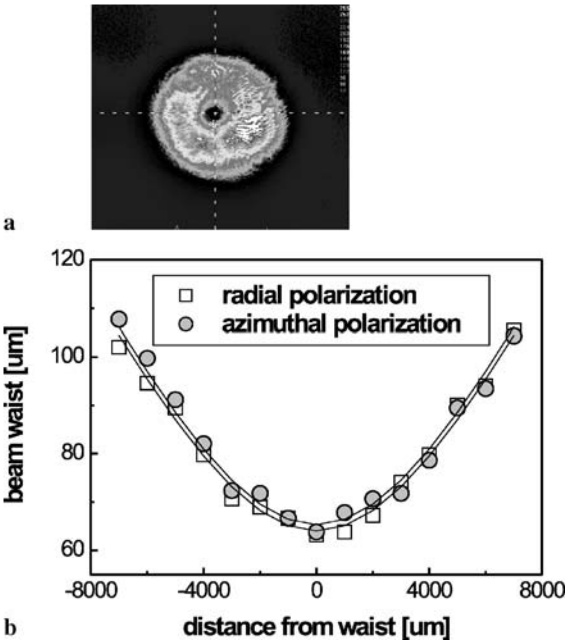

FIGURE 2 (**a**) Measured doughnut-like intensity profile. (**b**) Beam waist as a function of position relative to the focal point

a polarizer as a function of the polarizer angle. The degree of radial polarization was found to be better than 80%.

The radial polarization may be converted to an azimuthal state of polarization through an arrangement of appropriate phase-shifting elements such as two consecutive $\lambda/4$-wave plates or two consecutive 45° Faraday rotators. We have chosen the two Faraday rotators because the state of polarization can be switched from radial to azimuthal by simply reversing the second rotator, thus leaving all other parameters such as pulse energy etc., unchanged. The laser radiation was focused onto different targets by a single lens with a focal length of 100 mm and the longitudinal position of the focus was roughly in the middle of the material. Figure 2b shows the average beam waist at various positions before and after the focal point. Clearly, the intensity distribution for both states of polarization is almost identical. All targets were carefully aligned and their thickness was always less than the depth of focus. The measured hole diameters were on the order of 120–150 μm.

3 Results and discussion

3.1 *Introductory remarks*

While in laser cutting the absorption of light on the surface within the kerf is important [1], in laser drilling of high aspect ratio holes the reflection, waveguiding, and finally the absorption of radiation at the bottom of the hole, are of key relevance [14–19]. In view of this, it becomes clear that in both cases polarization of the radiation utilized plays a major role, although with different emphasis. In laser cutting it was found [1] that the most effective is the radial polarization and two main reasons have been identified. First, the energy deposition should be independent of the azimuthal angle, which rules out the linear polarization. Second, the energy deposition should be maximal, which is the case for the radial polarization. The radially polarized beam is always p-polarized with respect to the vacuum–material interface, whereas the azimuthally polarized beam is s-polarized and the circularly polarized beam is a mixture of both.

In laser drilling the situation is somewhat different and we start the discussion with a very simplistic, but intuitive, model. We first consider radially and azimuthally polarized laser radiation. Figure 3a shows the fraction of absorbed light for the radial (globally TM(p)) and the azimuthal (globally TE(s)) polarization as a function of the angle of incidence with respect to the vacuum material interface. Both polarizations possess cylindrical symmetry and, consequently, the absorption is independent of the azimuthal angle.

To simplify matters, we assume that the ablated depth per pulse increases with the absorbed fluence once a certain threshold is exceeded. Because the absorption for radially polarized light is always higher than for azimuthally polarized light, the ablated depth per pulse will always be larger. Furthermore, around the quasi-polarizing angle, radially polarized light is almost completely absorbed and ablation will be most effective. In other words, as the number of pulses increases, a depth profile is expected that lacks intermediate angles and becomes more and more box-like. In contrast, the

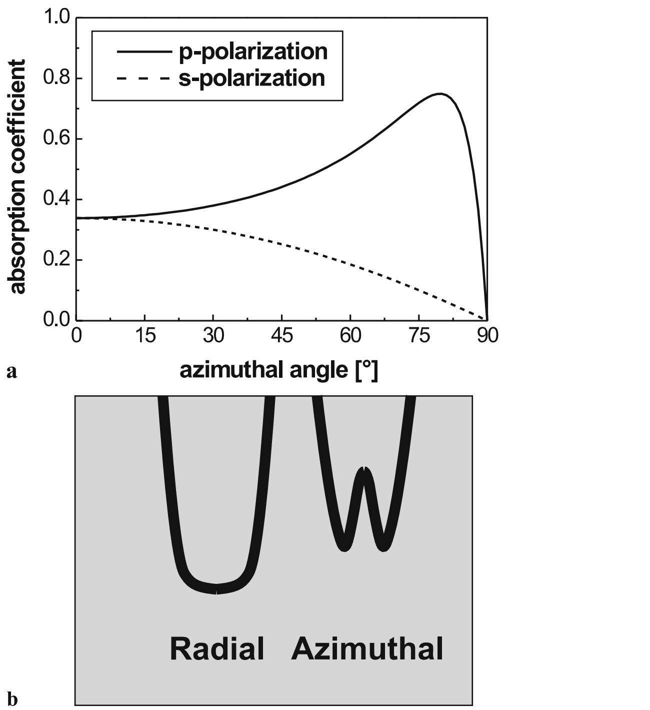

FIGURE 3 (**a**) Calculated absorption coefficients for radially (TM/p) and azimuthally (TE/s) polarized light for mild steel. (**b**) Expected hole cross sections

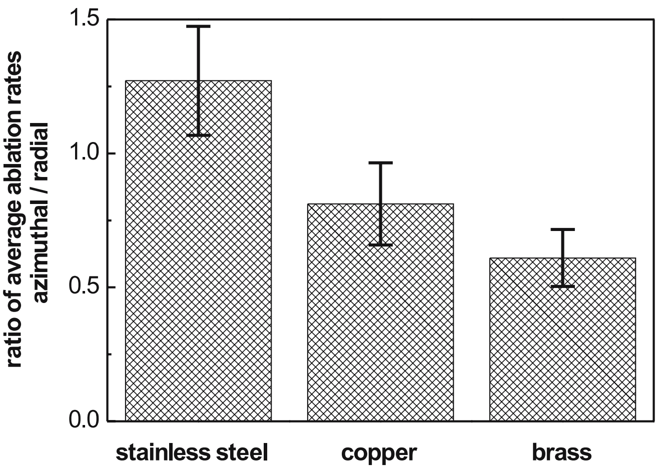

FIGURE 4 Ratio of average ablation rates for 1.5 mm of stainless steel, copper, and brass

absorption coefficient of the azimuthal polarization exhibits very little dependence on the angle of incidence and the depth profile should more or less resemble the intensity profile of the laser. The two scenarios are schematically depicted in Fig. 3b.

In order to test this simple model, the average ablation rates through 1.5-mm thick plates of mild steel, copper, and brass have been measured for radially and azimuthally polarized radiation. The average ablation rate was determined from the material thickness and the number of pulses necessary to drill through the material and serves as the figure of merit. Figure 4 shows the ratio of the average ablation rate for azimuthal over that for radial polarization. While the results for copper and brass are in reasonable agreement with the previously discussed intuitive scenario, the result for mild steel is clearly different from what has been expected. For copper and brass, the radial polarization yielded higher average ablation rates. However, azimuthal polarization was much more effective when drilling through mild steel. Thus, the model described above must neglect at least one important aspect of the process.

3.2 *Extended model*

It is known that for holes with a high enough aspect ratio, multiple reflections and waveguiding become important [19]. Especially when the absorption is relatively low, as in the case of metals, multiple reflections may cause a major redistribution of the energy deposition. Suppose the depth profile of a hole exhibits a ring-like structure as it would be expected for a doughnut-shaped beam profile. In what follows, we divide the incoming beam in a number of rays and inspect two scenarios. First, the energy deposition is determined by the first intercept of the incoming rays with the surface, thereby completely neglecting the influence of the reflected radiation. This scenario was also used in [1]. Second, we follow the rays on their way through the hole and calculate the energy absorbed at each intercept from the incident energy and the absorption coefficient and assume that after each intercept the reflected ray travels in the specular direction. For both scenarios, the ablation depth after each laser shot is then calculated from the energy deposition profile and subtracted from the previous depth profile. That is, all thermal aspects are integrated implicitly into the standard logarithmic ablation curves that have intentionally been set equal for the materials analyzed, except for the ablation thresholds that have been determined experimentally. Here, values of 3.4 J/cm^2, 1.3 J/cm^2, and 0.85 J/cm^2 have been utilized for mild steel, copper, and brass, respectively. These values are in good agreement with literature data [22–24]. The optical constants of the three materials were obtained from ellipsometry measurements.

The effect of multiple reflections or wave guiding becomes evident if one follows the evolution of the hole geometry (radial cross section) and the radial distribution of the absorbed fluence with increasing number of laser shots. The simulation results for mild steel are depicted in Fig. 5. Shown is the depth of the hole a) and b) and the absorbed fluence c) and d) as a function of radius for both polarizations. Initially, the radial polarization yields deeper holes but is later overtaken by the azimuthal polarization. This is accompanied by the onset of channelling of energy into the ring-like structure. In other words, after a certain number of shots, most of the azimuthally polarized light is guided towards the center of the ring leading to an even more effective drilling process. As seen in these model calculations, the fraction of absorbed azimuthally polarized light can be much higher than in the case of radial polarization (see Fig. 5c and d), thus, increasing the local ablation rate to a value well above the ablation rate for radially polarized light. Asymptotically, the results indicate that radially polarized light drills wider, box-like holes, while azimuthally polarized light tends to drill narrow channels.

The corresponding simulation results for brass are shown in Fig. 6. Compared to mild steel, the absolute reflectivities of brass for both polarizations are higher, however, the difference between the two reflectivity curves is smaller. Therefore, the light channeling effect is approximately equal for both polarizations and the local ablation rates do not show such a pronounced difference. The azimuthal polarization effectively loses its ‘channeling advantage’ with respect to radially polarized light and the higher absorption coefficient irrespective of the angle of incidence yields a higher average ablation rate for the radial polarization.

It must be mentioned that the whole scenario is fluence-dependent. For large fluences well above the ablation threshold, it is known that the ablation rate starts to saturate. Therefore, one expects that channeling of radiation leads to a markedly different ablation rate for the two polarizations only if the absorbed fluence is in between the threshold and the onset of saturation and if the difference in the absorption coefficients is large. As the incident fluence increases well above the onset of saturation, this regime is reached only when the holes exceed a certain depth.

3.3 *Systematic study*

The model described in the previous section aggregates all thermal effects into the ablation curves but neglects for example vapor/plasma formation and screening, and, thus, is still qualitative in nature. Nevertheless, we will show that the majority of the experimental trends in the accessible fluence regime can be qualitatively explained. Based on

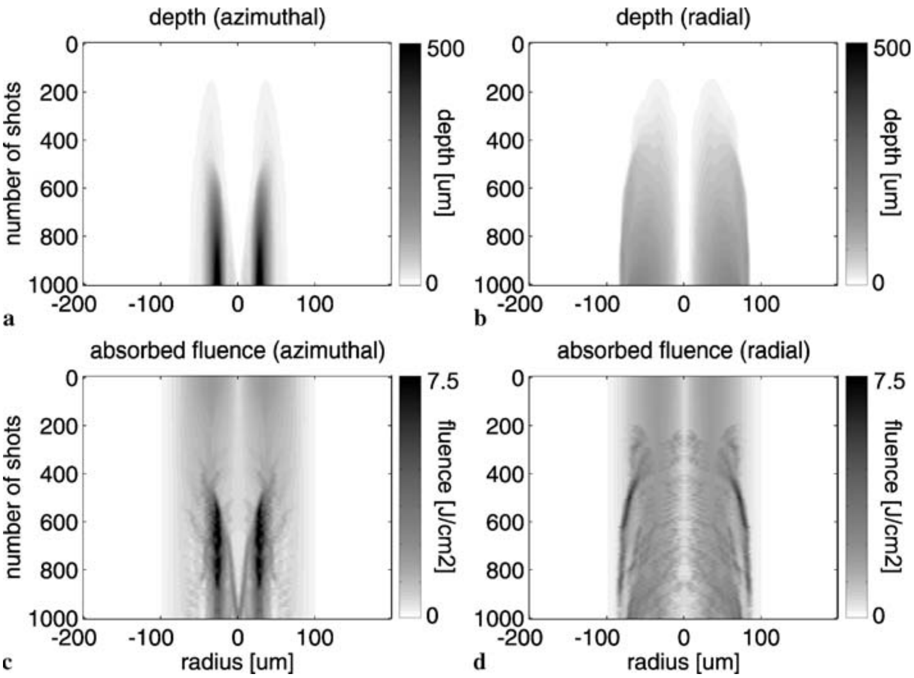

FIGURE 5 Simulated hole cross sections and corresponding absorbed fluences for mild steel taking account of multiple reflections. Evolution of the cross section, (**a**) and (**b**), and the absorbed fluence, (**c**) and (**d**), with increasing number of laser shots for azimuthal and radial polarization, respectively

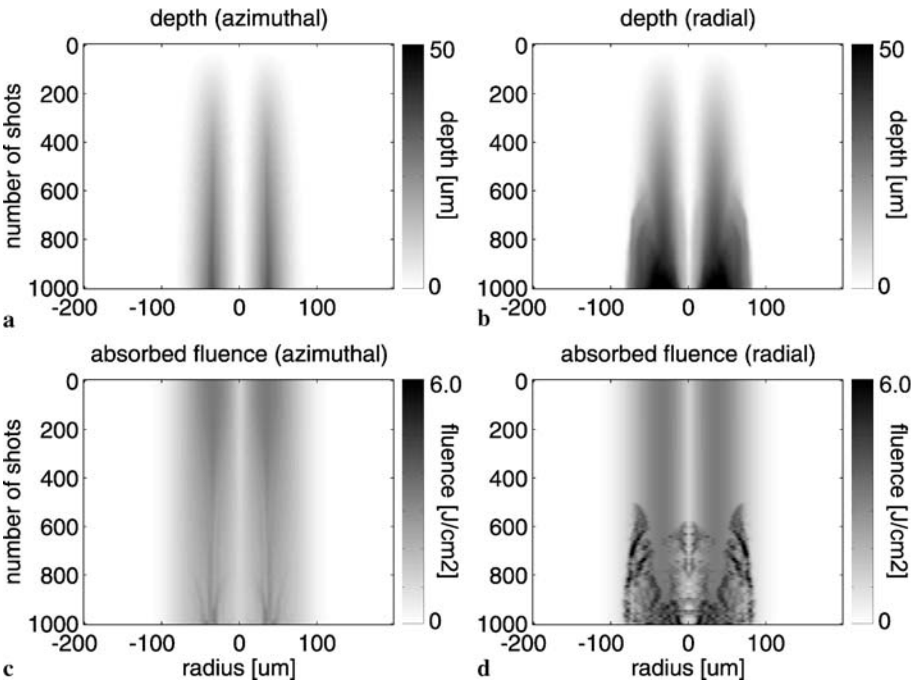

FIGURE 6 Simulated drilling of brass taking account of multiple reflections. Evolution of the cross section, (**a**) and (**b**), and the absorbed fluence, (**c**) and (**d**), with increasing number of laser shots for azimuthal and radial polarization, respectively

the previous results, brass and mild steel plates have been selected as targets for drilling experiments. In a first series of experiments the average ablation rate as a function of the fluence was investigated. Secondly, the average ablation rate was determined for various target thicknesses. Each data point corresponds to an average of seven subsequent experiments and the standard deviation is determined mostly by fluctuations in the laser output power. A summary of the experimental results is shown in Fig. 7a–d.

The average ablation rate for both brass and mild steel as a function of the incident fluence is shown in Fig. 7a and b. The material thickness was 1 mm. For both materials, and low fluences, azimuthally polarized light exhibits a larger average ablation rate than radially polarized light. Above a certain fluence the behavior reverses and the radial polarization becomes more efficient. For both brass and mild steel the crossover point is observed around the same fluence, namely 17.5 J/cm^2 for brass and 18.5 J/cm^2 for mild steel. The overall behavior, though, is different. For brass, the average ablation rate increases sharply above the ablation threshold, then decreases again, and finally saturates at a constant level. No such decrease is observed for mild steel where the average ablation rate grows continuously and then saturates on a level about an order of magnitude higher than for brass.

The results are in qualitative agreement with the model. For large fluences when the average ablation rate starts to

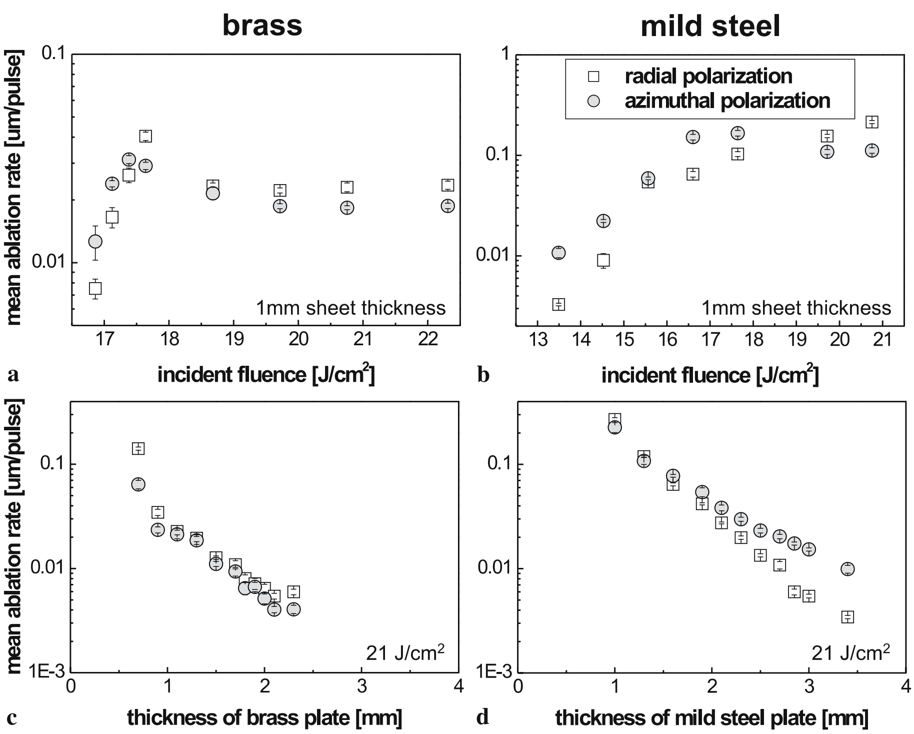

FIGURE 7 *Top row*: Average ablation rate as a function of fluence for (**a**) a 1-mm-thick sample of brass and (**b**) a 1-mm-thick sample of mild steel. *Bottom row*: Average ablation rate as a function of the material thickness for (**c**) brass and (**d**) mild steel. In both cases, the fluence was 21 J/cm^2

saturate, channeling of light plays a less dominant role and the radially polarized light becomes as efficient as and finally even more efficient than the azimuthally polarized light. This is true for both materials because the saturation of the ablation rate is mostly thermal in nature and not so much dominated by the optical properties of the material.

For a fluence of about 21 J/cm^2, which is the highest fluence available, the average ablation rate was determined as a function of the material thickness, as shown in Fig. 7c and d. In both cases, the average ablation rate decreases as the material becomes thicker, the details, however, are strikingly different. Radially polarized light is slightly more efficient irrespective of the thickness of the brass sample. On the contrary, for mild steel the two average ablation rates cross around 1.5 mm, and above this value the azimuthal polarization is more efficient than the radial polarization.

These results are again in coherence with the model, for brass channeling is approximately equal in both cases and the average ablation rate is mostly dominated by the higher absorption coefficient of the radial polarization. Thus, for all thicknesses, the radial polarization is more effective than the azimuthal polarization. For mild steel, however, the situation is different. The simulations have shown that after a certain number of laser shots, that is, once the hole has reached a certain depth, channeling of radiation by multiple reflections sets in for azimuthally polarized light and makes this polarization more and more efficient. This behavior is clearly observed in the experimental data shown in Fig. 7d. For thicknesses above approximately 1.5 mm, azimuthally polarized light gains over radially polarized light and the difference becomes larger as the material thickness increases.

The key findings of the study are summarily depicted in Fig. 8, and one may observe that experimental results and simulations are in qualitative agreement. In order to verify that

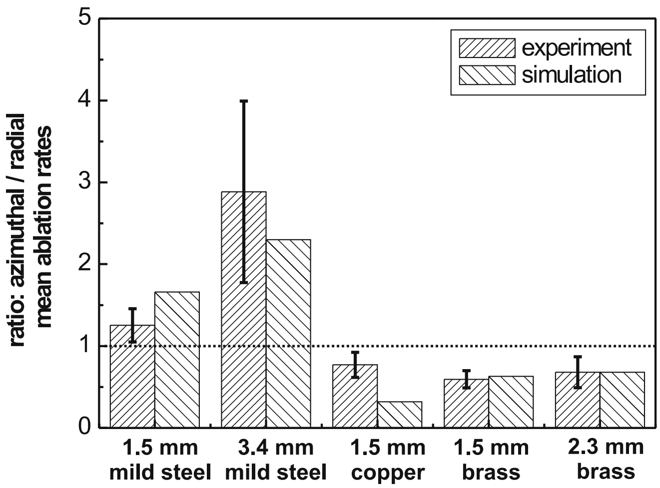

FIGURE 8 Comparison of experimental and simulation results for mild steel, copper, and brass

the experimental observations are dominated by the material's optical properties rather than by their thermal properties, a result for copper has been included in Fig. 8. Copper and brass have very similar optical properties, however, their thermal characteristics are significantly different. The fact that the ablation studies yield very similar results for both materials strongly suggests that thermal effects play only a minor role.

3.4 *Comparison to linearly and circularly polarized light*

To appreciate the values of the above findings, it is necessary to compare the results obtained with radially and azimuthally polarized doughnut-shaped radiation to ablation efficiencies obtained with standard light sources used in in-

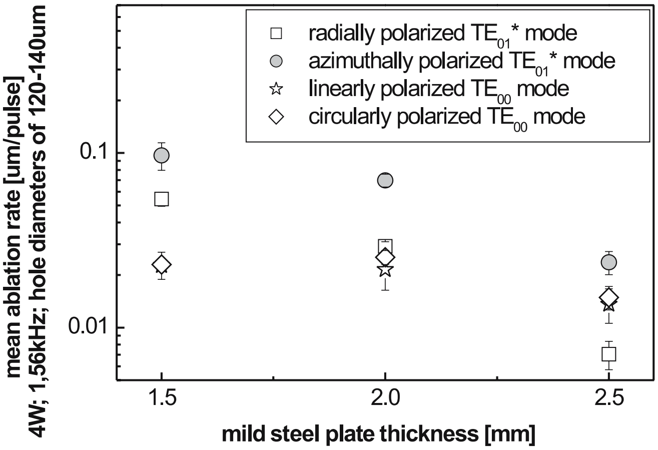

FIGURE 9 Average ablation rates for mild steel laser drilling with different modes of polarization as a function of sheet thickness

dustrial materials processing, that is, linearly or circularly polarized radiation with a Gaussian-shaped intensity distribution. The comparison criterion that has been selected here is the ablated volume, which was assumed to be equal in all cases by ensuring that entrance and exit holes had equal diameters. The pulse energies were identical in all experiments. The results of this comparison for mild steel are depicted in Fig. 9. In the considered range of sample thicknesses from 1.5 to 2.5 mm, azimuthally polarized light shows the highest drilling efficiency. As the holes gain depth, the advantage with respect to linearly and circularly polarized light shrinks. Radially polarized light shows higher efficiency than linearly or circularly polarized light only up to a depth of 2 mm. At 2.5 mm, it exhibits the lowest ablation efficiency.

An explanation for the initially higher drilling efficiencies of both doughnut-shaped radiation modes for up to 2 mm sheet thickness can be found in the intensity profiles of the ablating beams: the steeper edges of both doughnut mode beams ensure that less energy is wasted by sub-ablative interaction in the peripheral regions of the beam.

For deeper holes, the polarization distribution seems to become more important than the incident beam intensity distribution and we observe a behavior that is in accord with the line of argument of the preceding chapters. Linearly and circularly polarized beams occupy an intermediate position between purely *s*- or *p*-polarized radiation and lead to ablation efficiencies in between the ones obtained for azimuthally and radially polarized light.

4 Conclusion

We have demonstrated a Q-switched solid-state laser resonator with a doughnut-shaped and radially polarized transverse mode profile. The pulsed power was sufficient to drill holes into different metals and it was shown that, depending on the optical properties of the material and the depth of the keyhole, either azimuthal or radial polarization is more efficient. A comparative study with linearly and circularly polarized laser radiation shows that azimuthally polarized radiation drills holes of the same diameter and depth in mild steel with a 1.5 to 4 times higher efficiency, the exact value depending on the sheet thickness.

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