

LASER TECHNOLOGIES

PACS numbers: 42.62.Cf; 42.55.Lt; 42.60.Da
DOI: 10.1070/QE2009v039n02ABEH013890

Metal cutting by radiation from a CO_2 laser with a self-filtering cavity

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***Abstract*. The possibility of quality cutting by radiation from a CO_2 laser with an unstable self-filtering cavity (SFC) is experimentally investigated. The SFC provides the product of the divergence angle by the beam radius close to that for lower modes in a stable cavity (SC), however, at a higher radiation power, which favours faster cutting. In the far-field zone, the SFC beam has a diffraction structure with side maxima, which is usually considered as a negative factor in laser cutting. 25-mm-thick steel slabs have been cut. The comparison of the obtained results with known data on SC lasers shows that the principal characteristics of the cut (the width, edge roughness, specific expenditure of energy) are close in these lasers. A conclusion is made that at the chosen cavity parameters, the specific spatial structure of the SFC laser beam has no significant effect on the cut characteristics.**

Keywords: *industrial laser, laser cavity, beam quality, laser cutting, cut quality.*

1. Introduction

Laser cutting of metals is presently a well developed industrial process successfully employed in practice. It combines a high speed and high quality of cutting. The speed of cutting and the maximum width of slabs to be cut increase with the laser power. The power of the lasers used for cutting, among which flow CO_2 lasers with a stable optical cavity (SC) hold the lead, have been growing for the last two decades by approximately 1 kW per five years and achieves now 6 kW [1]. Laser cutting is performed by a focused beam with the focal spot diameter of ~ 0.1 mm, the required radiation intensity being maintained along a distance comparable with the thickness of the slab to be cut. This entails the requirement for a sufficiently high quality for the laser beam, namely, the BPP parameter (Beam Parameter Product, the beam radius in the near-field zone multiplied by the angular radius of the beam in the far-field zone) should not exceed 6 mm mrad [1]. In a CO_2-laser, the beam with this quality can only be obtained upon generation at lower transverse modes (TEM_{00} or TEM_{01^*}), which is the main reason limiting the power of CO_2 lasers used for cutting. A higher power requires a greater Fresnel number of the cavity, which leads to excitation of higher transverse modes and increase in the BPP parameter.

The possible employment of such types of solid-state diode-pumped lasers as fibre lasers (FLs) is being actively studied now [2 – 4]. Due to a shorter radiation wavelength compared to CO_2 lasers, FLs exhibit the required BPP even in the multimode regime. Presently, the power of 10 kW is obtained with the BPP parameter acceptable for cutting. Experiments on steel cutting show that FLs provide faster cutting compared to CO_2 lasers at a similar radiation power [2 – 4]. Nevertheless, the roughness of the cut surface, which is often taken as an indicator of the cut quality, is approximately twice greater when cutting thick slabs by FLs [4]. Possible reasons may be specificity of the radiation absorption at the wavelength of 1.06 μm in the cut channel [2] or a narrower cut width than in the case of CO_2 laser [3]. Thus, presently known results give no indications on definite advantages of FLs in laser cutting of highest quality.

On the other hand, metal cutting by CO_2 lasers is characterised by high quality [5, 6] and the radiation power can be increased by using other pump schemes and optical cavities instead of the SC, provided the BPP parameter is kept constant. In lasers with diffuse [7] or convective [8] cooling of the active medium, the hybrid cavities – unstable in one coordinate and stable or waveguide in another – are successfully used. In a hybrid cavity, radiation is usually coupled out through a lateral face of the plane in which the cavity is unstable. Due to the diffraction at a sharp edge of the output mirror a beam in the far-field zone has a specific structure in the form of a central spot and side maxima.

Presently formulated requirements to the beam quality are based on its integral characteristic, namely, PBB and do not take into account the intensity distribution in the focal spot. The most general requirement to the laser beam is its 'compactness', i.e. a small part of the total beam energy should correspond to low-intensity peripheral regions [5]. A stable cavity meets this requirement sufficiently well. The presence of a complicated diffraction structure is usually considered as a negative factor. In the case of a CO_2-laser with a hybrid cavity, the beam spatial structure is first corrected by extracavity spatial filtering. However, presently there are no qualitative criteria for making allowance for the role of the spatial structure. In monographs and reviews on laser cutting, for example, [5, 6, 9, 10] this problem is not

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Received 23 April 2008; revision received 15 September 2008
Kvantovaya Elektronika **39** (2) 191 – 196 (2009)
Translated by N.A. Raspopov

considered. Hence, the appropriateness of a particular beam generated by a laser with a specified cavity and mode ensemble for cutting requires special investigation.

The authors of papers [11, 12] reported the employment of high-power CO_2 lasers with a self-filtering cavity (SFC) [13], which refers to the type of cavities with a Fourier transform or FT-cavities [7]. Due to intracavity spatial filtering, the SFC allows one to generate a radiation beam close in quality to the TEM_{00} mode. Because of a large volume of the lowest mode, the radiation power may be two – three times greater than that in a laser with a stable single-mode (TEM_{00}) cavity of the same length. In [11], the quality parameter BPP for the laser beam is 4.7 and the maximum radiation power is 8 kW. A project on designing a 14-kW laser has been developed in [14].

Output beams in the SFC and in the stable cavity have different spatial structures. Radiation is extracted from SFC via reflection from a circular highly-reflecting mirror, whereas in the SC it passes through a whole semitransparent mirror. Due to diffraction in the pin-hole of an output mirror, the focused beam in the SFC has a specific diffraction structure with side maxima in the waist and the cross-section intensity distribution varies as the beam propagates in space. In a focused beam the intensity distribution has different forms in the waist and vicinity. Details of the spatial distribution in the focal region depend on the cavity parameters. The question concerning the quality of cutting by a laser with the SFC has been open so far.

In this paper, we study characteristics of the cut performed by radiation from a CO_2 laser with the SFC without spatial filtering. The obtained results are compared with known data on CO_2 lasers with a stable cavity and on fibre lasers.

Results of numerical calculations of output parameters for SFCs are presented. Experiments on cutting low-carbon steel, stainless steel, and titanium by radiation from a CO_2 laser with the SFC are performed. Basic characteristics such as the speed of cutting, cut width, and surface roughness are determined.

2. Parameters of the output beam for a self-filtering cavity

The SFC (see Fig. 1) is a confocal cavity comprising two confocal spherical mirrors with different curvatures, in the common focal plane of which the circular output mirror with the pin-hole of radius $a = (0.61\lambda f_2)^{1/2}$ is placed. The active medium resides between the output mirror and the mirror with the focal length f_1. Due to strong mode loss discrimination for higher modes the lowest mode is reliably selected in the cavity.

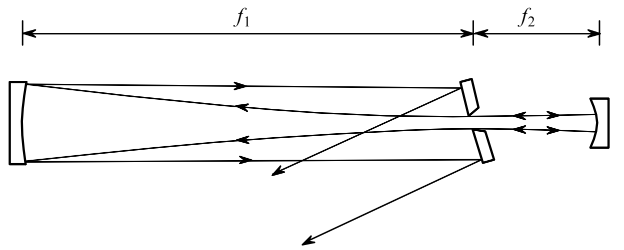


Figure 1. Optical scheme of a SFC.

Based on the diffraction Fresnel – Kirchhoff integral, the cross-section radiation intensity distribution of the SFC output beam was calculated by the Fox – Lee iteration method. Figures 2 and 3 present the distributions of the intensity I over the beam radius r on the output mirror and at the distance of 3 m from it. Figure 4 shows the angular intensity distribution in the far-field zone. In the near-field zone, the output beam has a circular cross section with the internal radius a and the external radius of about $1.5Ma$ ($M = f_1/f_2$ is the magnification factor for the cavity). For comparison, the dotted line shows the intensity distribution for a Gaussian beam. Due to diffraction on the output mirror, the shape of the intensity distribution in the SFC beam varies with the distance from the output mirror acquiring a specific structure with a central spot and side maxima in the far-field zone. The quality of the output beam increases with decreasing the relative dimension of the hole in the output mirror, i.e. as M rises. Figure 5 presents the calculated fraction ε_0 of the total beam energy corresponding to the central spot and the intensity I_{m1} of the first side maximum relative to the central intensity as functions of the cavity magnification M.

At $M > 4$, the central spot comprises more than 90 % of all the beam energy and the intensity of the first side maximum relative to the central intensity is below 0.5 %. Note for comparison that a source with a circular aperture and uniform distribution of amplitude and phase has $\varepsilon_0 = 84$ % and $I_{m1} = 1.75$ % [15].

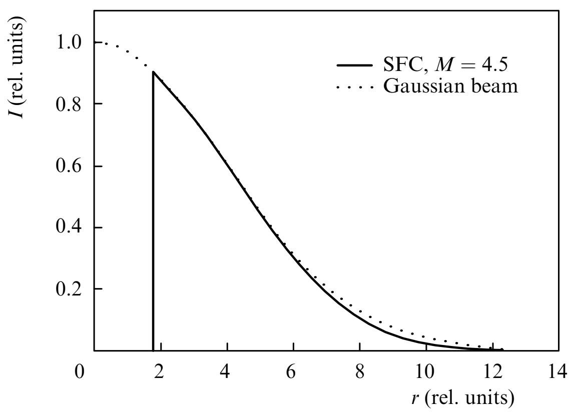


Figure 2. SFC output beam intensity distribution in the near-field zone.

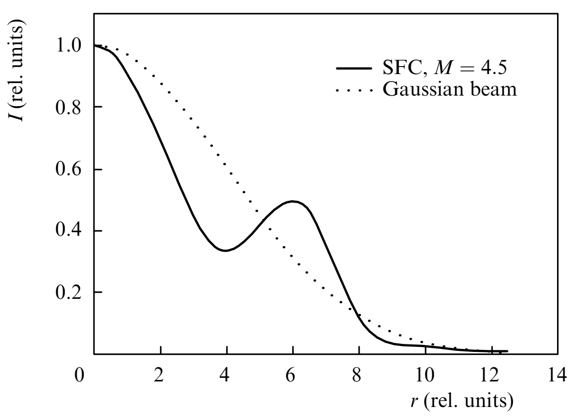


Figure 3. SFC output beam intensity distribution at a distance of 3 m from the output mirror.

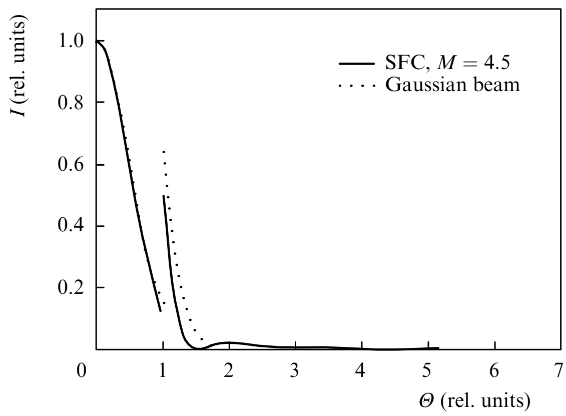


Figure 4. SFC output beam intensity distribution versus the angle Θ in the far-field zone (the peripheral part of the distribution is scaled).

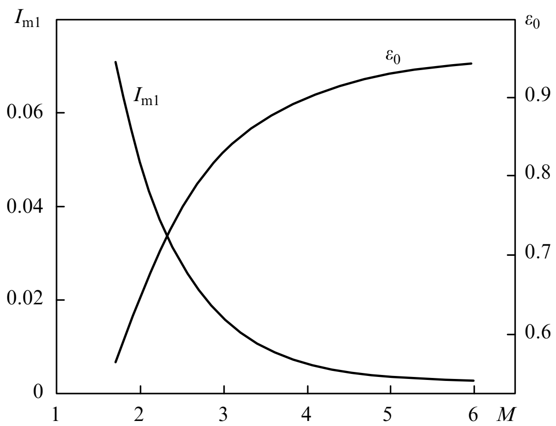


Figure 5. Intensity I_{m1} of the first side maximum relative to the intensity at the axis and the fraction ε_0 of energy in the central spot relative to the total beam energy versus the geometrical cavity magnification M.

One can see that the differences in the shape of intensity distributions for Gaussian and SFC beams in the far-field zone are substantial in peripheral regions only, where the radiation intensity is low. At greater M the output SFC beam becomes similar to the Gaussian beam. However, in this case the cavity feedback coefficient R' decreases ($R' \simeq 2/M^2$), which worsens the energy conversion efficiency in the cavity and limits the parameter M. Estimates and experiments show that at $M = 4 - 4.5$ and the corresponding feedback parameter in a multipass cavity of a low-pressure CO_2 laser, the high efficiency of energy conversion can be provided.

3. Results of experiments on laser cutting of steel and titanium slabs by radiation from a CO_2 laser with a SFC

The experiments were carried out with a cw CO_2 laser [11] having a self-filtering cavity. The cavity magnification was 4.5 and the beam diameter at the cavity output was 50 mm. An external telescope reduced the beam diameter down to 30 mm. The laser radiation was linearly polarised, and then it was transformed to a circular polarisation by an external phase-shifting mirror. The cutting equipment included a two-coordinate table with a program control and a cut head stabilised to the slab surface by means of a capacity sensor. Cutting was performed using a traditional scheme: radiation was focused on a sample to be cut by a single lens made from ZnSe and an assisted gas flowed parallel to the beam.

At the lens focal length of 190.5 mm the focal spot diameter was measured by a device comprising a moving reflecting cylinder and a photodetector [5, 16]. (Scanning by a reflecting cylinder is equivalent to slit scanning.) The result is presented in Fig. 6. The focal spot base diameter is 330 μm and the half-height diameter is 125 μm.

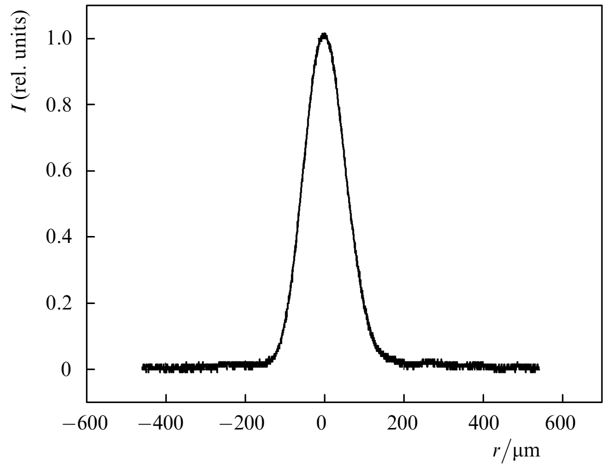


Figure 6. Intensity distribution in the waist of the focused beam at the lens focal length of 190.5 mm.

The axial intensity grows almost linearly with the radiation power (see Fig. 7) and the shape of the intensity distribution remains almost constant in the power range 1 – 5.5 kW.

Low-carbon steel, stainless steel, and titanium slabs were cut. The most of experimental data were obtained for low-carbon steel, which is the most commonly encountered material for laser cutting. A sufficiently great amount of experimental data on low-carbon steel is published, which allows one to make a more complete comparison.

In the experiments, we determined the cut surface roughness and width, i.e. the parameters, which are often considered basic characteristics of the cut quality.

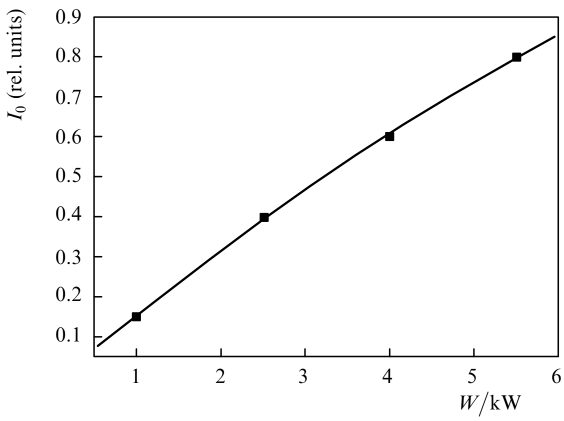


Figure 7. Intensity I_0 at the centre of focal spot versus the radiation power W.

Low-carbon steel. Slabs of thickness from 1.5 to 25 mm were cut. Oxygen was used as an assisted gas. The slab thickness t, radiation power W, lens focal length f, and oxygen pressure P in the cutting head are presented in Table 1.

The cut parameters were chosen such that the surface roughness R_z of the cut was minimal. The roughness was measured with a Rank Taylor Hobson profilometer (Form Talysurf series) in two cross sections at the distances corresponding to 1/3 and 2/3 of the slab thickness from the upper slab surface. For sample characterisation, the greater value was taken. In most cases, greater roughness was observed in the lower part of the cut, which determined the sample quality.

Table 1. Conditions of cutting low-carbon steel of thickness t.

t/mm	W/kW	f/mm	P/kg cm^{-2}
1.5	0.5–1	127	1
3	0.5–1	127, 190	1
5	0.5–3	127, 190	0.5
10	1.2–3	190	0.5
16	1.7–3	190	0.5
20	3–4.5	190, 254	0.4
25	4–4.5	254	0.35

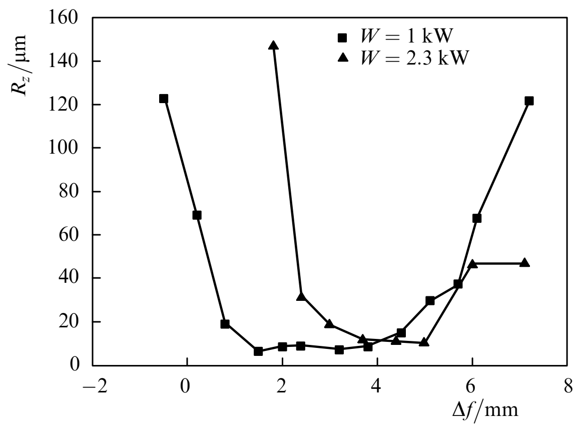


Figure 8. Cut surface roughness versus the beam waist position Δf relative to the upper slab surface at t = 5 mm, f = 190.5 mm, and various values of W.

The experiments were performed as follows. At a chosen slab thickness t, the parameters W, f, and P were fixed. Then, the beam focal position Δf relative to the slab surface and the cut speed υ were determined at which the parameter R_z is minimal. The cut width b corresponding to minimal R_z was determined. The cut width was measured, similarly to [6] by a probe. For all thicknesses presented in Table 1, cuts without burr were obtained with edges close to straight ones.

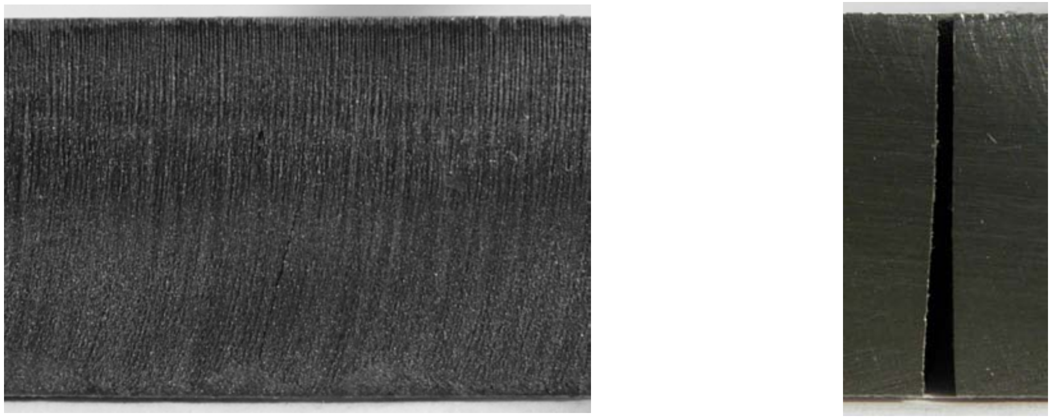
For example, the dependence of the cut surface roughness on the position of the beam focus Δf relative to the slab surface is shown in Fig. 8. Positive values of Δf correspond to the focus position above the slab. The optimal value of Δf increases with the radiation power, so the cut width does.

The cut surface and cross section of its channel for the 16-mm-thick slab are shown in Fig. 9. Table 2 presents the measurement results for the minimum cut surface roughness and the corresponding cut width for slabs of various thicknesses. Specific results for a CO_2 laser with a stable cavity borrowed from [6] are also given in the table. The radiation power and cut speed obtained with the SFC are given in parentheses in Table 2. One can see that for low-carbon steel the cut width and surface roughness are close in the cases of CO_2 lasers with stable and with self-filtering cavities.

The energy efficiency of laser cutting can be characterised by the parameter $W/\upsilon t$ sometimes called the separation energy, which is the expenditure of the radiation energy per unit area of the cut lateral surface [5, 17]. In our experiments the parameter $W/\upsilon t$, which corresponds to minimal roughness rises with t. The mean value of $W/\upsilon t$

Table 2. Minimal roughness of the cut surface and the corresponding cut widths in cutting low-carbon steel slabs of thickness t.

t/mm	b/mm (W/kW; υ/m min^{-1})		R_z/μm (W/kW)	
	SFC	SC [6]	SFC	SC [6]
5	0.23 (1; 1.5)	0.2–0.3	8 (1)	6
10	0.48 (1.8; 1.1)	0.35–0.4	17 (1.8)	28
16	0.63 (2.5; 0.9)	–	27 (2.5)	28
20	0.68 (4; 0.7)	0.5	40 (4)	28



a b

Figure 9. Cut surface (a) and cross section of the cut channel (b) in low-carbon steel; t = 16 mm, W = 2.5 kW, υ = 0.9 m min^{-1}.

Table 3. Cut widths and surface roughness in cutting stainless steel slabs of thickness t.

t/mm	b/mm (W/kW; υ/m min^{-1})		R_z/µm (W/kW)			Δf/mm
	SFC	SC [6]	SFC	SC [6]	FL [4]	SFC
10	0.19 (4.5; 1.3)	0.3	–	43	60 (4)	−13
16	0.26 (4.5; 0.32)	0.3	42 (4.5)	–	80 (4)	−20
20	0.54 (5; 0.25)	0.5	–	–	–	−20

for various radiation powers varies from 8.2 J mm^{-2} at $t = 3$ mm to 15.7 J mm^{-2} at $t = 20$ mm.

Data from various papers concerning the separation energy in cutting low-carbon steel with the use of oxygen at the slab thickness of up to 20 mm are collected in [17]. For the mean value authors give 9.5 J mm^{-2} and all the data are within the range 6–13 J mm^{-2}. This suggests that the energy characteristics of cutting with SFC and SC lasers are similar.

Stainless steel. In cutting stainless steel, nitrogen is used as an assisted gas at the pressure of 12 kg cm^{-2} in the cutter chamber.

The cut width and surface roughness for stainless steel samples are presented in Table 3. The cut surface at $t = 12$ mm is shown in Fig. 10. It follows from Table 3 that the cut width and surface roughness are the same for samples treated by CO_2 lasers with SFCs and SCs. The surface roughness in the case of a FL is 1.5–2 times greater. The fact that the FL exhibits the greater roughness than the CO_2 laser in cutting stainless steel was mentioned in [2–4]. As follows from [2] the similar thing is observed with low-carbon steel.

Figure 10. Cut surface of stainless steel; $t = 12$ mm.

Titanium. The cross section of a cut channel in a 20-mm-thick titanium slab is shown in Fig. 11. Cutting was performed in the argon flow at the radiation power of 4 kW with the lens focal length of 254 mm. The cut surface of 30-mm-thick titanium slab at the radiation power of 6 kW and the cut speed of 0.1 m min^{-1} is shown in Fig. 12.

The results of the experiments on cutting low-carbon and stainless steel allow one to make a conclusion that at optimal SFC parameters of a low-pressure CO_2 laser the characteristic diffraction structure of the laser beam has no substantial effect on the cut quality. The roughness of the cut surface, its width, and specific expenditure of the laser energy in cutting are close to those for a CO_2 laser with a stable cavity. However, an SFC laser can generate greater power at a high beam quality. This provides a higher cut speed. The maximal speed gain may be obtained with thin slabs where radiation is focused to a spot of minimal dimensions. In cutting thick slabs, the high beam quality makes it possible to employ long-focal lenses and produce the narrow extended focal domain with a required power density. In this way, the narrow cut can be obtained with almost straight walls. This advantage is noticeably revealed in cutting metals in a flow of the inert gas when the beam focus is close to the bottom surface of the slab. For example, in cutting 20-mm-thick titanium slabs the cut width measured at half-thickness does not exceed 0.3 mm (see Fig. 11).

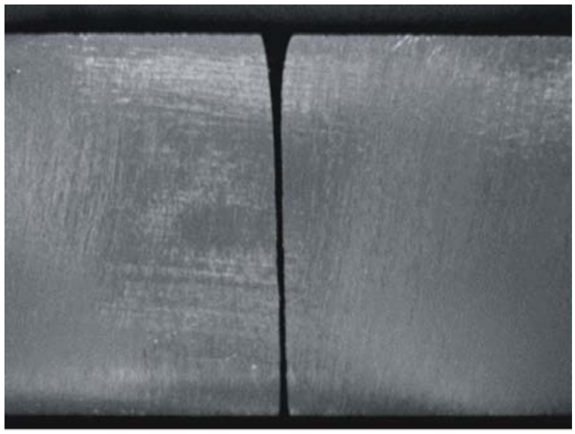


Figure 11. Cross section of the cut channel in a 20-mm-thick titanium slab; the lens focus is on the bottom surface of the slab.

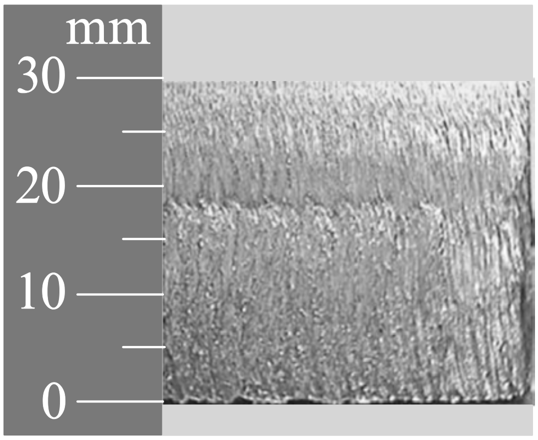


Figure 12. Cut surface of a 30-mm thick-titanium slab.

4. Conclusions

Results of experiments on laser cutting of low-carbon and stainless steels by the radiation from a CO_2 laser with a self-filtering cavity are presented. The possibility of obtaining a high-quality cut without spatial filtering is shown. The comparison with published results for a stable cavity shows that the cut width, surface roughness, and specific expenditure of energy are approximately the same for SFC and SC lasers. Thus, at properly chosen cavity parameters the specific spatial structure of the SFC beam has no substantial effect on the characteristics of cutting. Nevertheless, due to a large mode volume a CO_2 laser with the SFC can generate at lowest modes approximately two – three times greater power than a CO_2 laser with the SC. The obtained results illustrate promising prospects for using SFC lasers in highly-efficient laser cutting systems requiring high brightness of the laser beam.

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