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SPECIFIC FEATURES OF LASER CUTTING OF STEEL SHEETS AND MONITORING OF SAMPLE QUALITY AFTER LASER INFLUENCE

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An automated laser system with an 8-kW *quantum generator with the beam quality not worse than that of a single-mode laser is described. The possibility of using such a system in procurement production for cutting carbon and stainless steel sheets is demonstrated. The quality control of the blank material shows that the properties of the latter satisfy appropriate standards.*

Key words: *industrial gas lasers, self-filtered resonators, gas-laser cutting of metal sheets, technological parameters, structure and properties of blanks.*

Introduction. Among laser technologies currently used in machine-building branches of industry, gas-laser cutting of metal and nonmetal materials has found the widest application [1–3]. The use of laser cutting in procurement production turned out to be most effective [1]. A wide range of thicknesses and grades of materials being cut and almost arbitrary parameters of blanks being cut allow manufacturing blanks of various types, sizes, and geometry.

The main advantages of laser cutting are as follows:

— improvement of processing quality owing to the minimum area of thermal influence, reduction of heat-induced strains, absence of the force action on the article;

— higher processing rate (severalfold higher than that in conventional methods of mechanical treatment);

— severalfold reduction of time needed for the preparatory stage of production in the case new articles are to be produced;

— higher material utilization rate owing to the use of optimal cutting patterns;

— high quality of cutting of structural steels, which often allows butt welding without prior mechanical treatment;

— no displacements of the cut edges;

— possibility of producing articles with notches in the form of acute angles, junctions without radii, and thin bridge connections (less than 1–2 mm thick), as well as small-diameter orifices (in contrast to die-cutting by universal circular tools).

Using the laser-cutting technology, one can cut sheeted materials over a complicated contour with accuracy ranging from 100 to several micrometers.

Advanced laser cutting systems allow cutting thin-sheeted materials with a velocity up to 120 m/min with an error smaller than 100 μm. To reach a maximum possible thickness of sheets being cut and a maximum possible cutting velocity, the laser power should be increased; therefore, the technology of laser cutting with a power of 5 to 6 kW has been recently conquered in industry.

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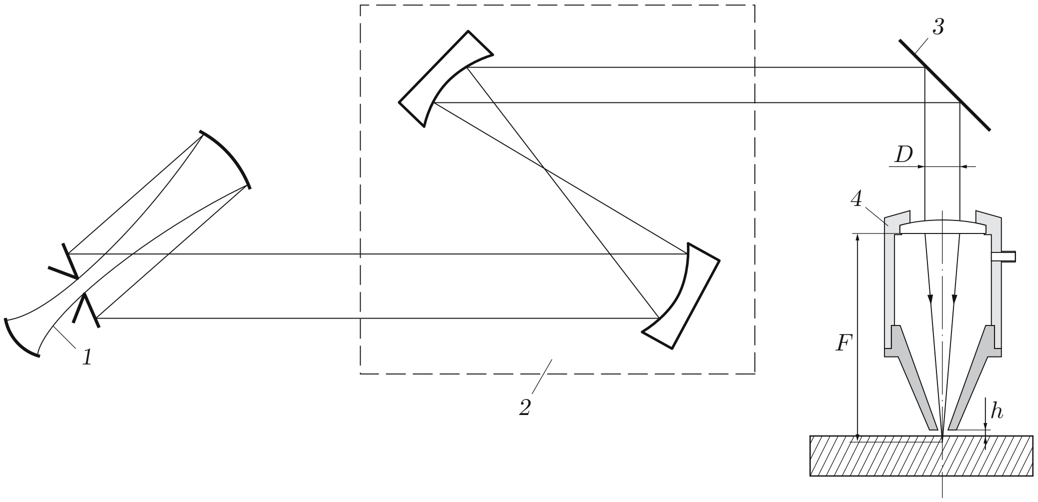

Fig. 1. Experimental setup: 1) laser with a self-filtered resonator; 2) beam guide; 3) polarizer; 4) cutter.

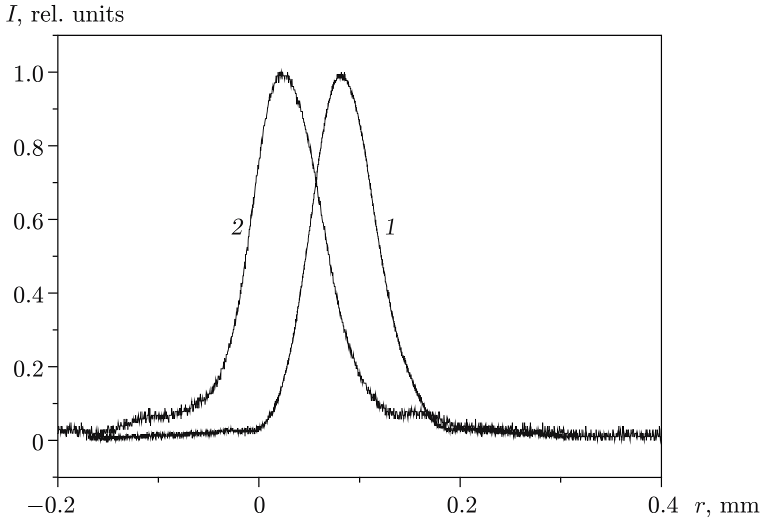

Fig. 2. Distribution of radiation intensity in the focal spot: 1) undistorted beam; 2) beam with distortion.

The basic parameters of an industrial laser are its power and beam quality. It is well known that the requirements of high power and high beam quality are contradictory [4]. Most industrial lasers involve the use of stable resonators; therefore, modes of higher orders are excited with increasing laser power, which impairs the beam quality. To resolve this contradiction, Gobbi and Reali [5] proposed to use a self-filtered unstable resonator (SFUR) in the industrial CO_2-laser. By using such a resonator, the authors of [6–8] managed to obtain a laser power higher than that in a laser with a single-mode (TEM_{00}) resonator of the same length and to retain the beam quality corresponding to a laser with a single-mode resonator.

The present paper describes the results of development of a laser cutting technology with the use of a powerful CO_2-laser with a self-filtered resonator.

Experimental Setup and Parameters of Metal Cutting. To improve the cutting technology, we used an automated industrial laser system developed at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences on the basis of a continuous CO_2-laser with a power up to 8 kW [9–11]. The laser includes a multipass self-filtered resonator capable of providing high-power radiation with a diverging factor close to the diffraction value [6–8].

The experimental setup is schematically shown in Fig. 1. The beam diameter at the cutter entrance can be corrected by a mirror telescope included into the beam guide. The radiation is focused with the use of a lens (ZnSe) with a focal distance of 190.5 mm. The distribution in the lens focus was measured by the rotating cylinder method [12]. Figure 2 shows the distribution of radiation intensity in the focal spot of the beam used for cutting (curve 1). The measurements were performed with a laser power of 5.5 kW. The overall shape of the distribution and the size of the focal spot remain unchanged in the entire range of power, whereas the axial intensity increases linearly with increasing power [11]. In the course of experiments, the distribution in the focal spot was periodically monitored to reveal possible distortions introduced by the focusing lens or by elements of the optical system. An example of a distorted beam is also shown in Fig. 2 (curve 2). Such a distribution ensures cutting of worse quality. The experiments were performed with an undistorted beam only.

The laser cut was formed by a joint action of the laser beam and an oxygen jet onto the metal. The jet was generated in a conical nozzle with a constriction angle of 30°. To ensure high-quality cutting, the setup implies the possibility of varying the nozzle diameter within 0.5 to 3.0 mm, the gas pressure (up to 16 atm), and the position of the lens focus with respect to the plane of the sheet being cut. Metal cutting is performed on a technological table, which ensures two-coordinate programmable motion of the cutter with a velocity up to 50 m/min. The distance between the nozzle exit and the sheet plane was established and automatically sustained by a capacitance sensor. The range of the gap in the tracking mode was 100–2000 μm.

The materials to be tested were low-carbon steel St. 3 and Cr–Ni stainless steels 12Kh18N10T (Russian analogs of M1020 steel and 304 steel in the American classification, respectively). The main objective of the research was to establish dependences of the cutting velocity, cutting width, and quality of the cut surface on the laser power. These parameters were chosen because the cutting velocity determines the productive capacity of the system, the cut width determines metal losses, and the state of the cut surface determines whether the articles or blanks can be used without additional mechanical treatment.

Figure 3 shows the cutting velocity for carbon steel versus the laser power used and the thickness of the material processed. The upper and lower boundaries of the cutting velocity were measured. The upper boundary is defined as the limiting velocity at which the lower edge of the cut is not completely cut through or restores its integrity immediately after the beam has passed, which impairs the quality of the lower edge. The lower boundary of the cutting velocity is characterized by the beginning of autogenous cutting and by dramatic worsening of the quality of the cut surface. The lower boundary could not be registered for a sheet 1.5 mm thick. It is seen in Fig. 3 that the upper boundary of the cutting velocity increases linearly with increasing laser power, whereas the lower boundary remains almost unchanged (for a fixed material thickness). Naturally, high-velocity cutting modes are preferable from the viewpoint of production efficiency. Yet, the final choice of the cutting regime should be made with allowance for the quality of the cutting surface.

An important parameter of cutting is the cut width. This quantity is related both to the laser power used and to the cutting velocity. Figure 4 shows the cut width in the M1020 stainless steel 5 mm thick as a function of the cutting velocity for different laser powers. The cut width decreases with increasing cutting velocity and increases with increasing laser power (Fig. 5). The measurements performed allow us to determine the specific energy of radiation for different thicknesses of the material being cut $P = W/(Vdh)$. The specific energy necessary for a unit volume of steel to be heated to the melting point and to melt is estimated as 12 J/mm^3.

The specific energy of radiation monotonically decreases with increasing thickness of the material being cut (Fig. 6). The measured value of P, however, is higher than the estimated value. We can assume that the decrease in the specific energy of radiation in cutting blanks of large thickness may be caused by a more effective use of the oxygen jet.

To illustrate the changes in the cross-sectional shape of the cut, Fig. 7 shows the photographs of the cuts made in a steel sheet 5 mm thick with a cutting velocity of 1.2 m/min, which were obtained with different laser powers. The cut channel is somewhat expanded at the end. The cut shape and width are clearly seen to depend on the laser power applied. The presence of expanding and constricting segments of the cuts and non-straight-line boundaries can also be mentioned.

Mechanical Properties and Structure of Samples after Laser Cutting. Gas-laser cutting of thin metal sheets is most effective. It is necessary to verify, however, that cutting produces no adverse effect on the properties of the material being processed. For this purpose, two lots of sheets subjected to laser cutting in an

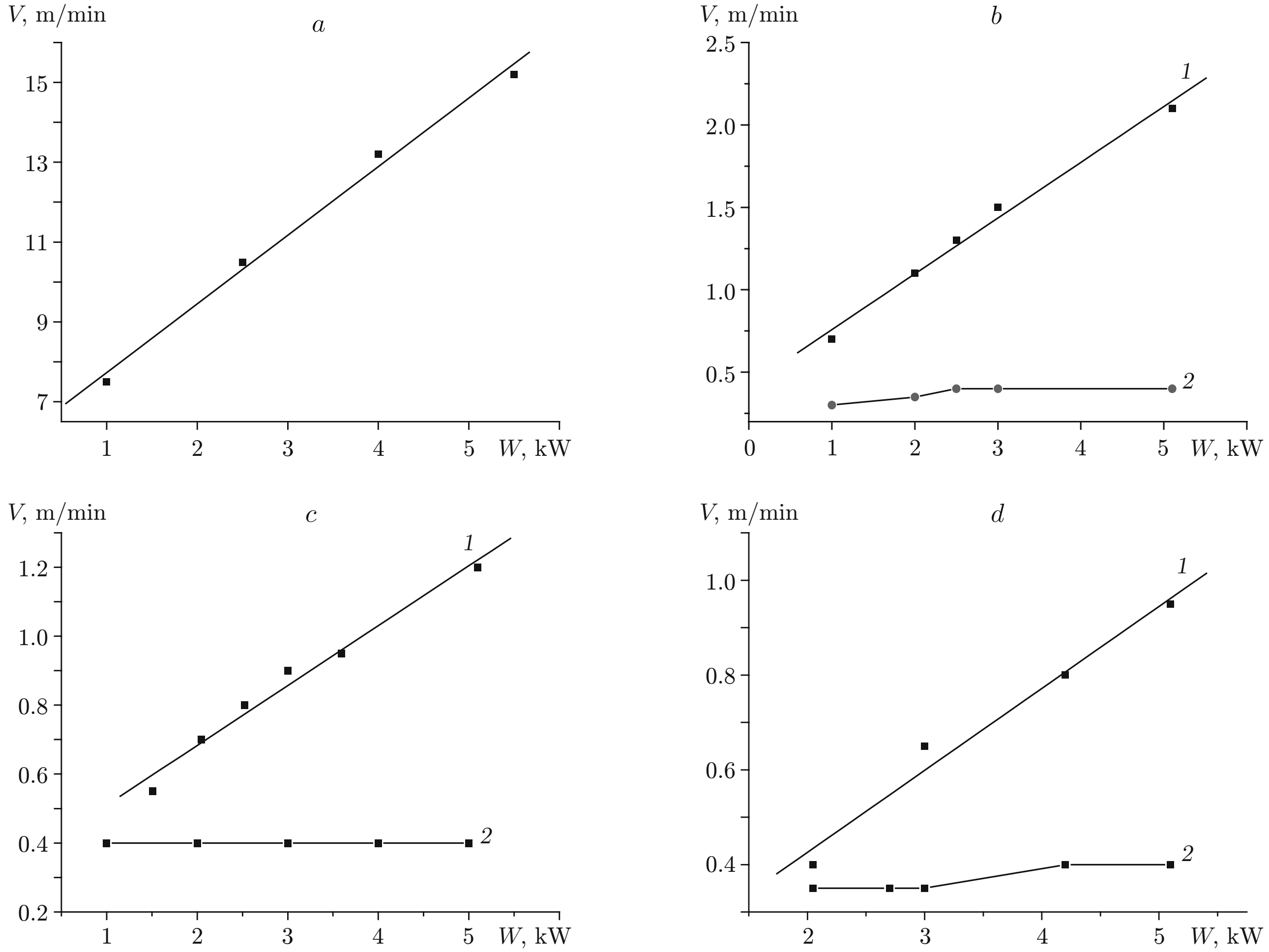

Fig. 3. Cutting velocity versus laser power for sheets of different thickness: $d = 1.5$ (a), 10 (b), 16 (c), and 20 mm (d); curves 1 and 2 are the upper and lower boundaries of the cutting velocity, respectively.

oxygen environment were prepared: M1020 steel samples with a sheet thickness of 1.5 mm in the first lot and 304 steel samples with a sheet thickness of 1.0 mm in the second lot. Rectangular samples 100×10 mm were examined. The samples were subjected to tensile tests in an Instron-1185 universal testing machine with a strain rate of $5 \cdot 10^{-4}$ sec^{-1} (the velocity of the moving grip was 1 mm/min). The tests were performed at room temperature.

It was found that samples made of stainless and carbon steels under chosen conditions yield strain curves without specific features, such as a “tooth” and “yield area;” hence, a conventional rather than a physical yield point was determined [13].

The results of mechanical tests of the samples after laser cutting are summarized in Tables 1 and 2. The time resistance and the dimensionless elongation at failure for M1020 steel (Table 1) satisfy the requirements of the Russian State Standard GOST 16523-70: breaking strength $\sigma_{\text{b}} = 370$–480 MPa and $\delta \geqslant 22\%$ [14]. The conventional yield point for the Russian analog of M1020 steel sheets is not designated. According to [15], however, it should be higher than 205 MPa. Mechanical properties of the 304 steel samples (Table 2) are significantly higher than the requirements of GOST 5582-75: conventional yield point $\sigma_{0,2} \geqslant 205$ MPa, breaking strength $\sigma_{\text{b}} \geqslant 530$ MPa, and $\delta \geqslant 40\%$ [14]. For one sample made of M1020 steel, the value of $\sigma_{0,2}$ was below 205 MPa, which could be caused by an adverse microstructure of the material formed after gas-laser cutting.

The microstructure was studied with the use of transverse metallographic sections. The metallographic sections were produced in a traditional manner: mechanical grinding, mechanical polishing by the diamond paste with the mean grain size of 10 μm, and chemical etching. The sections were analyzed on a Neophot-21 microscope.

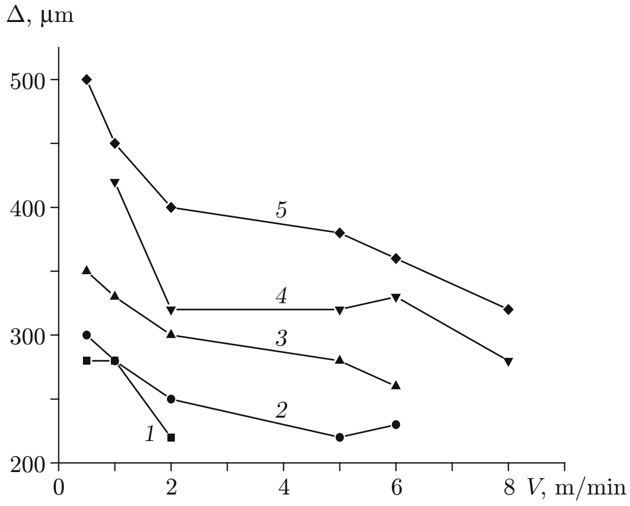

Fig. 4

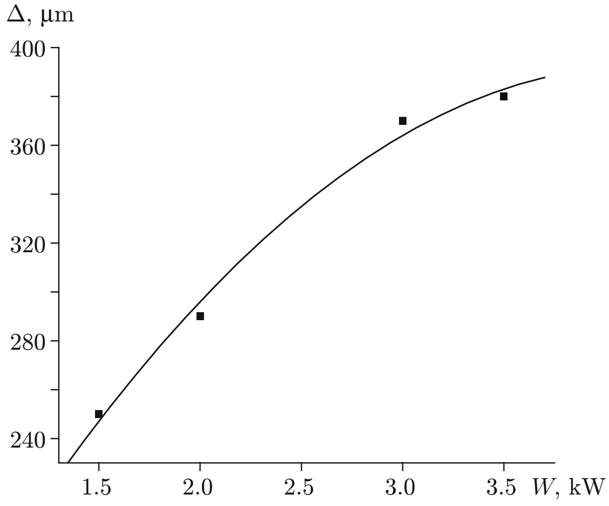

Fig. 5

Fig. 4. Cut width versus the cutting velocity for different laser powers ($d = 5$ mm): $W = 0.75$ (1), 1 (2), 1.5 (3), 2 (4), and 3.5 kW (5).

Fig. 5. Cut width versus the laser power ($d = 5$ mm and $V = 2$ m/min).

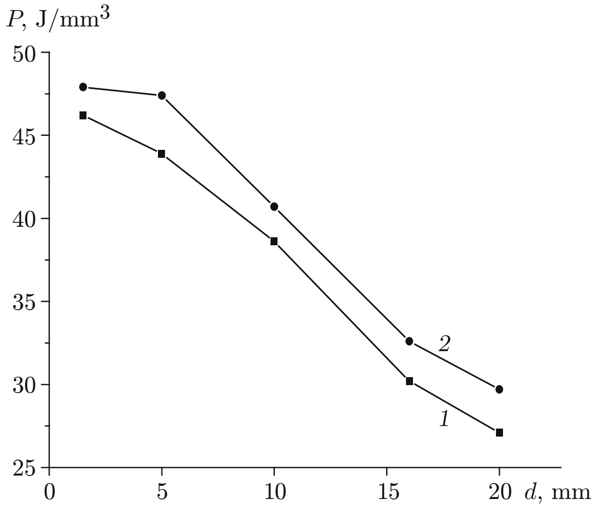

Fig. 6. Required energy contribution versus metal thickness for laser powers $W = 2$ (1) and 3.5 kW (2).

TABLE 1

Mechanical Properties of M1020 Steel Samples

With the thermal influence zone				Without the thermal influence zone			
Sample No.	$\sigma_{0,2}$, MPa	σ_b, MPa	δ, %	Sample No.	$\sigma_{0,2}$, MPa	σ_b, MPa	δ, %
1	191.2	392.8	32.0	4	205.6	381.5	47.0
2	226.0	403.5	37.8	5	200.9	385.4	42.2
3	226.0	401.3	36.1	6	226.8	397.1	37.6
Mean value	214 ± 20	399 ± 5.5	35.3 ± 3	Mean value	211 ± 14	388 ± 8	42.2 ± 5

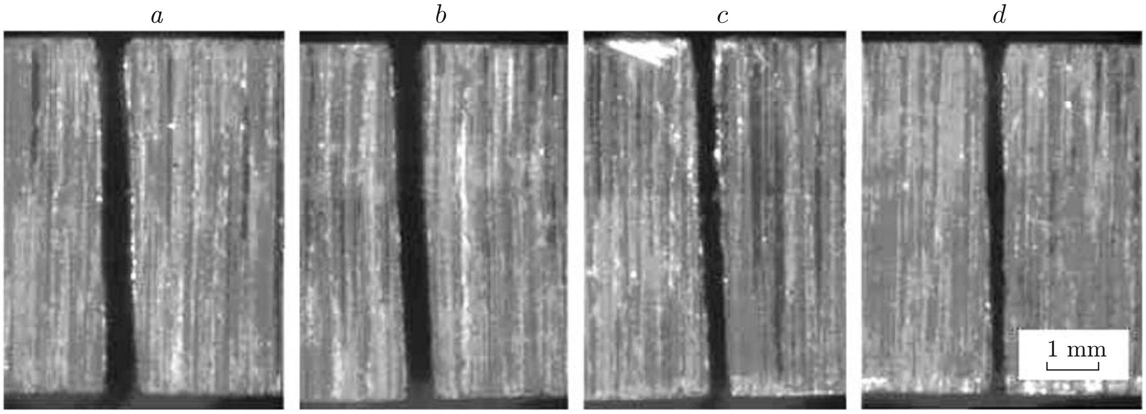

Fig. 7. Shapes of cuts in a steel sheet 5 mm thick for laser powers $W = 3.5$ (a), 3 (b), 2 (c), and 1.5 kW (d).

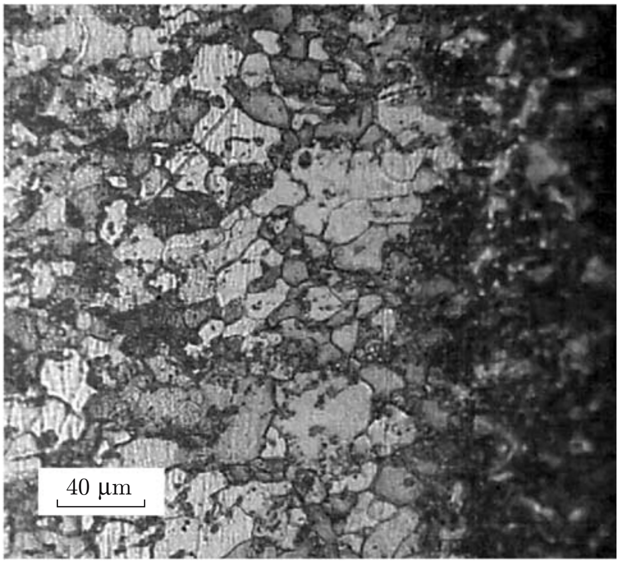

Fig. 8

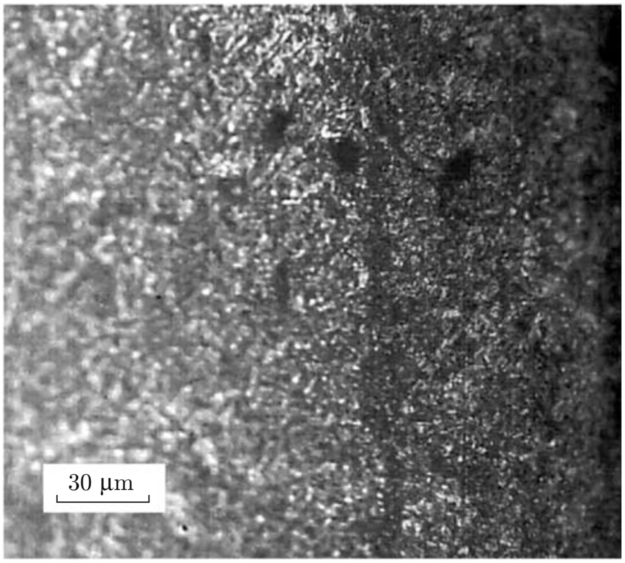

Fig. 9

Fig. 8. Microphotograph of the transverse metallographic section of the M1020 steel sample after laser cutting.

Fig. 9. Microphotograph of the transverse metallographic section of the 304 steel sample after laser cutting.

M1020 steel samples were etched in a 4-% alcohol solution of HNO_3, and 304 steel samples were etched in the chlorazotic acid (75% HCl + 25% HNO_3).

It is seen from Fig. 8 that the M1020 steel samples have a ferrite–pearlite structure. The ferrite grains and pearlite colonies have a polyhedral morphology. The thermal influence zone is etched more profoundly and is clearly visible in the microphotograph. An analysis of the structural characteristics of the material (Table 3) allow us to conclude that the grains in the thermal influence zone become much finer, which, apparently, is responsible for an almost twofold increase in microhardness.

A typical structure of 304 steel samples is shown in Fig. 9. There is also a thermal influence zone here, but its transverse size is smaller than that in M1020 steel samples (approximately 75 and 90 μm, respectively). The grains in the thermal influence zone are not as fine as in M1020 steel samples. It should also be noted that the grain size of the basic metal in 304 steel samples was approximately 5 μm, which was substantially smaller than the size of the ferrite grain in M1020 steel samples (approximately 17 μm).

TABLE 2

Mechanical Properties of 304 Steel Samples

With the thermal influence zone				Without the thermal influence zone			
Sample No.	$\sigma_{0,2}$, MPa	σ_{b}, MPa	δ, %	Sample No.	$\sigma_{0,2}$, MPa	σ_{b}, MPa	δ, %
1	431.5	886.8	80.8	6	403.0	877.0	80.0
2	449.2	869.7	77.6	7	385.8	868.2	76.4
3	—	876.3	74.8	8	427.9	875.0	81.6
4	451.3	868.4	59.0	9	407.6	872.2	77.6
5	447.3	868.4	76.4				
Mean value	444 ± 9	874 ± 8	73.7 ± 8	Mean value	406 ± 17	873 ± 4	79 ± 2

TABLE 3

Structural Characteristics of M1020 Steel Samples after Gas-Laser Cutting

Segment of the sample	a, μm	b, μm	H, MPa
Basic metal	17.1	87.5 ± 7	1109 ± 118
Thermal influence zone	2.1	—	2077 ± 148

Note. a is the mean size of the ferrite grain, b is the width of the thermal influence zone, and H is the microhardness.

The results of microstructural studies allow us to assume that the mechanical properties of M1020 steel samples could be affected by the presence of the thermal influence zone. To check this assumption, the thermal influence zone of some samples was removed by milling (200 μm on each long side). After that the mechanical characteristics of such samples were determined (see Table 1). Removal of the thermal influence zone exerted practically no effect on the strength properties of M1020 steel. Only an increase in plasticity approximately by 20% can be noted. Obviously, a certain decrease in plasticity after laser cutting is caused by a higher microhardness of this zone (see Table 3). In both states, however, the mean mechanical characteristics satisfy the requirements of GOST 16523-70. The presence of samples with a rather low yield point is caused by specific features of the initial material.

As it could be expected, a similar operation with 304 steel samples did not exert any effect on the mean mechanical properties of the material (see Table 2).

Conclusions. The automated industrial system based on a CO_2-laser with a power up to 8 kW with a self-filtered resonator, which was developed at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences, can be effectively used in procurement production for cutting carbon and special steel sheets. Such a system allows cutting of blanks from sheets up to 20 mm thick with a velocity up to 1 m/min, following a prescribed program. The error in blank sizes is within 100 μm, and the quality of the cut surface is so high that no additional mechanical treatment is required. The study of mechanical characteristics and microstructure of the blank material after gas-laser cutting shows that this operation does not worsen the metal properties; hence, correcting thermal finishing is not necessary.

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