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THE ANALYSIS OF LASER THERMOSPLITTING OF FRAGILE MATERIALS BY USING OF SPECIAL GEOMETRY BEAMS

ANALIZA TERMICZNEGO ROZSZCZEPIENIA MATERIAŁÓW KRUCHYCH ZA POMOCĄ WIĄZEK LASEROWYCH O SPECJALNEJ GEOMETRII

In this paper the numerical modeling of allocation of thermoelastic fields which are formed during controllable laser thermosplitting in fragile nonmetallic materials is executed within the limits of theory of elasticity. Modeling is executed for laser beams with a cross-section in the form of an ellipse, a circle, and the semi-ring and theirs combination. The classical circuit of realization of the given method consists of the superficial heating of a material by a laser beam and the aftercooling of this zone by means of a refrigerating medium. Thus the crack which is organized in the zone of refrigerating medium supply follows a laser beam along a treatment line. On the basis of thermoelastic fields allocation shown, that application of the classical circuit of the given method realization with the use of elliptic beams possesses a number of the disadvantages, one of which is the quick deflection of a crack from a line of influence of a laser beam and refrigerating fluid at treatment close to collateral border of the sample. Thus the crack is progressed in a direction to collateral border of the sample. It is displayed, that application of special geometry beams allows to diminish degree of effects of a treatment line closeness to boundary line of the sample on crack development. The positive effect is attained by forming a compression stress zone not only ahead and under field of a refrigerating medium effects where the crack is initialized and explicated, but also on each side of zone of a refrigerating medium effects, that in one's turn does not allow a crack to be deflected aside.

Keywords: laser cutting, thermoelastic stresses, crescent beam, crack

W pracy przedstawiono wyniki obliczeń numerycznych rozkładu pól termosprężystych, powstających w procesie kontrolowanego laserowego termicznego rozszczepienia kruchych materiałów niemetalicznych. Obliczenia, zgodnie z teorią sprężystości, wykonano dla wiązek laserowych o przekroju eliptycznym, pierścieniowym, pół-pierścieniowym oraz ich kombinacji. Klasyczna metoda praktycznej realizacji eksperymentu polega na powierzchniowym rozgrzaniu materiału wiązką laserową i następnie schłodzeniu rozgrzanego obszaru chłodziwem. Przy takim postępowaniu, w obszarze schładzanym powstaje mikropęknięcie. Wzrasta ono za wiązką laserową, wzdłuż linii obróbki materiału. Na podstawie analizy rozkładu pól termosprężystych wykazano, że klasyczny schemat realizacji eksperymentu, z wiązką o przekroju elipsy, cechuje wiele niedoskonałości. Jedną z nich jest duże odchylenie od linii oddziaływania wiązki laserowej, przy obróbce materiału w pobliżu krawędzi próbek. Dowiedziono, że zastosowanie wiązek laserowych o specjalnej geometrii, zmniejsza wpływ powierzchni granicznej próbki na generację mikropęknięcia. Poprawę jakości obróbki materiału uzyskać można w wyniku powstania naprężeń ściskających nie tylko w obszarze schładzanym, gdzie powstaje i rozwija się mikropęknięcie, ale także z obu bocznych stron wiązki laserowej. Wówczas nie jest możliwa propagacja mikropęknięcia w kierunku bocznym.

1. Introduction

Method of controllable laser thermosplitting is one of the most effective and exact precision methods of separation of products of brittle nonmetallic materials. A number of papers [1-4] is devoted to given method. The classical scheme of realization of the given method is presented in Figure 1 and consists of the surface heating of a material by a laser beam 1 and the subsequent cooling of this zone by means of a coolant 2. As a result in the area of coolant feeding the crack which follows a laser beam along a treatment line is organized [1, 2]. Final division is fulfilled by mechanical, thermal or ultrasonic finish chopping.

Previously, authors had carried out finite-element solution of a problem on allocation of the thermoelastic fields arising in a sheet silicate glass in the process of controllable laser thermosplitting with use of CO_2–

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laser [5-9] the scheme of which is presented in Figure 1. The problem is solved in quasistatic statement according to [10].

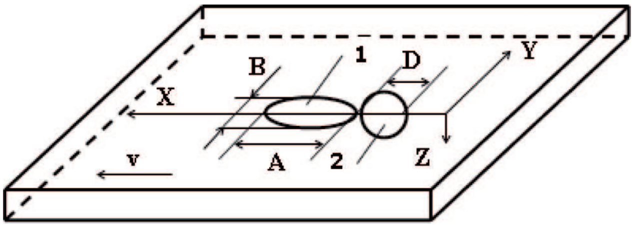

Fig. 1. The layout of an elliptic laser beam and coolant in a treatment plane

The analysis of allocation of σ_{yy} stress fields showed, that in the zone of a laser beam considerable in values compressive stresses are formed. In front and in the depth of a material is enveloped by a zone of tensile stresses. In top layers of the sample one more zone of the tensile stresses which location is defined by localization of a coolant impacts is formed. The given zone of tensile stresses at the bottom is restricted by the compressive stresses formed by a laser beam.

As a result of the analysis of thermoelastic fields allocation it is established that initiation of a dividing crack occurs in blankets of a material from crack similar microstructure defect in a zone of the tensile stresses formed owing to feeding of a coolant. Further the initial crack begins the movements and is spread to a zone of the compressive stresses formed by laser radiation. After that nonstationary growth of a crack stops, and its further development is defined by a modification of a spatial distribution of zones of the compressive and tensile stresses, which caused by relative movement of a treated material, a laser beam and a coolant.

However the given scheme has a shortcoming. In that case, when a line along which heating and cooling material is carried out (axis X in Figure 1) disposes close to side boundary of the sample, at presence on its edge of microdefects it is observed a sharp deviation of a crack from a treatment line towards side boundary up to the boundary, and the subsequent extinction of development of a crack. For this reason it is necessary to realize cutting on remote distance from side boundary that increases an amount of waste products in manufacturing.

According to it searching new or modification of already existing methods of division of brittle nonmetallic materials allowing to perform treatment maximum close to edges of the sample is represented actual.

2. Problem statement

For calculation of thermoelastic fields arising in samples from brittle nonmetallic materials in the process of controllable laser thermosplitting the finite element method realized in software product ANSYS is used. Now the application area of the given method is very extensive and covers all physical problems which are described by differential equations. Its essential advantage at modelling of laser technological processes is the possibility of problem solving with any body geometry, with the mixed boundary conditions and with a glance of materials properties dependence on temperature. Thus we consider a spatial distribution of intensity of laser radiation on cross-section of bundles of various geometry and its volume absorption a worked stock.

All calculations are carried out for samples from silicate glass with geometrical sizes 40×40 mm and thickness of 3 mm. The calculations were considered that glass density is fixed and equal ρ=2450 kg/m^3. Dependence of thermal conductivity and a specific heat from temperature have been considered [11]. The coefficient of elasticity, Poisson's ratio and thermal expansion coefficient relied accordingly equal E=68 GPa, ν=0.221, α=89·10^{-7} (1/°C). Highly dispersed air water mixture feeding on a material surface under pressure is selected as a coolant. At used parameters of feeding of air-water mixture cooling of a glass surface with heat-transfer coefficient equal to 6800 watt/m^{2}K is ensured [12]. The treatment speed of material for all proposed below schemes of realization of process of controllable laser thermosplitting v is selected equal 15 mm/sec. Low value of a treatment speed in calculations is selected for convenience a picture representation and the analysis of a spatial distribution of elastic stress fields in a glass plane-parallel plate. Increasing of a treatment speed provokes a contraction on plate depth a zone of tensile stresses caused by coolant impact, and enveloping it below a zone of compressive stresses caused by material heat, and also displacement of these zones towards material blankets. In turn it provokes inconvenience for qualitative illustrative representation of patterns of fields. The basic measure of optimization of technological parameters on the basis of the information on temperature fields is value of maximum temperature in work area which defines the mechanism of fracture of the sample. In case of silicate glasses treatment as an upper bound of permissible temperatures at which the fragile mechanism of separation is realized, value of a glass-transition temperature (for a leaf silicate glass – 789K) serves.

As laser thermosplitting stipulates realization of brittle failure, the modelling of respective processes as fracture criterion of a material expediently use of tensile strength of silicate glass. While analyzing the process of initiation and development of a crack ultimate strength has been chosen equal 25 MPa [11, 12].

3. Finite element analysis

Calculations of thermoelastic fields formed in the process of controllable laser thermosplitting for laser beames with a cross-section in the form of an ellipse, a semiring and crescent-shaped beams have been carried out for the comparative analysis.

Modelling of process of controllable laser thermosplitting by using of an elliptic beam according to scheme presented in Figure 1 is carried out. In Figure 2 the spatial distribution of thermoelastic fields σ_{yy} is presented to the fixed instant. So long as beam and coolant movement are carried out in the middle of the sample in view of symmetry on both sides from plane Y=0 the fields pattern is presented for half of sample. Thus the forward edge of the sample represents a cut in plane Y=0. As a radiation source it is used CO_2-laser with a wavelength λ =10.6 microns which corresponds to an intensive absorption blankets of the sample and power P=30 W. Sizes of major and small axes A=10 mm and B=5.4 mm respectively. Diameter of a coolant impact field of on a surface of material D=3 mm also remains invariable in all methods proposed lower. Maximum calculation values of temperatures of the sample do not exceed 747 K.

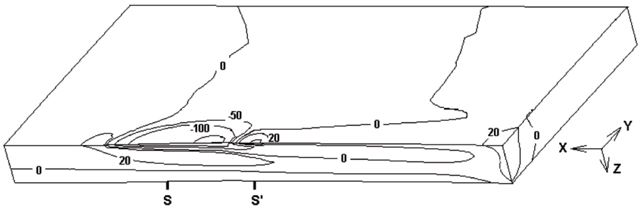

Fig. 2. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample by using of an elliptic laser beam

Centers position of a laser beam and a coolant along an axis X mark in Figure 2 by positions S and S′ accordingly. The analysis of the spatial distribution of thermoelastic fields σ_{yy} presented on figure shows, that as it has been told earlier, in the area of coolant impact there is a zone of the considerable tensile stresses. Thus volumes of tensile stresses exceed ultimate strength of glass.

In this zone the crack is initialized and developed. In front and below this area is restricted by a zone of the considerable compressive stresses formed by a moving laser beam. However on one side this field is not restricted by the strong compressive stresses, especially when treatment is carried on along boundary of the sample or in immediate proximity to it.

Microdefects and microcracks on boundaries of the sample are concentrators of stresses. Therefore at treatment near the side boundary of the sample in apexes of cracks and microdefects zones of considerable in value tensile stresses are formed and the direction of the main crack development switches towards the given microdefects and microcracks. To remove the given effect is reasonably to shape a zone of considerable in value compressive stresses not only in front and below zones of the tensile stresses formed by a coolant, but also in each side of it.

Calculation of the elastic stress fields arising in the process of one-beam controllable laser thermosplitting at use of CO_2-laser bundle with a cross-section in the form of a semiring has been carried out. The scheme of realization of the given method is presented in Figure 3. The position 1 marks the shape of a laser source spot on a material surface, by a position 2 – a coolant. External and internal radiuses of ring R=2.5 mm r=1.6 mm. Laser radiation power P=20 W. Centers of a semiring and a zone of action of a coolant are coincide.

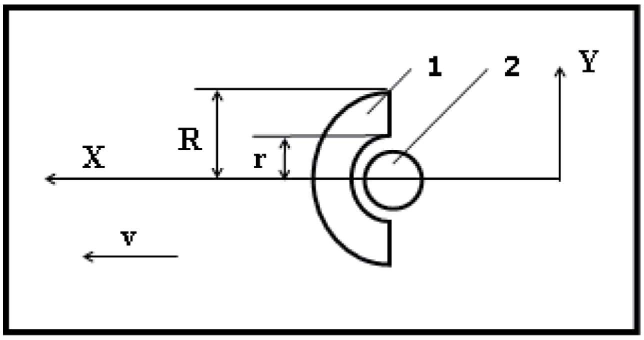

Fig. 3. The layout of a semiring laser beam and a coolant in a treatment plane

In Figure 4 the spatial distribution of thermoelastic fields σ_{yy} arising at realization of the given scheme is presented. The pattern of fields is presented for half of plate and for more visualization is presented in an expanded scale for a plate part. Position S in figure displays a location of a laser bundle center and a coolant along axis X. In the area of laser radiation impact on a surface of the sample there is a zone of the strong compressive stresses which restricts field of a coolant impact not only in front and below a coolant, but also on one side. However it is necessary to note, that maximum values of temperatures on a material surface 738K are formed not on a line, along which treatment moves (an axis X), but along the edges of a laser beam, and along a line of treatment values of temperatures in 150 degrees lower than maximum values. Low values of temperatures along a treatment line, and also slight along axis X the warm-up area leads to that in the area of a coolant feeding stresses σ_{yy} does not develop into the tensile.

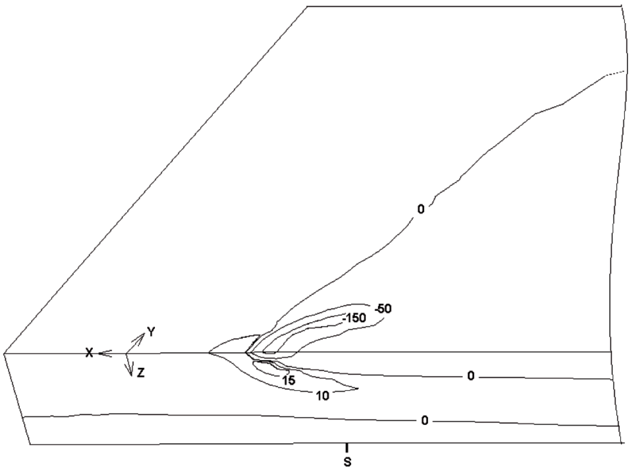

Fig. 4. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample by using of a semiring laser beam

Earlier authors in papers [14-17] had received outcomes on two beam laser thermosplitting of the brittle nonmetallic materials which essence consists in a simultaneous irradiation of a processed sample by two laser beams, with different lengths of the waves, one of which corresponds to an intensive absorption blankets of the sample, and the second corresponds to a volume absorption processed material. The developed technology of two beam thermosplitting of brittle nonmetallic materials provides a possibility of forming given distribution of thermoelastic stresses not only in a thin blanket, but also in all depth of a treatment material. In turn it ensures quality rising and accuracies of proceeding considerably reduces deviations of a crack from a line of separation of a material at the expense of increasing of its depth.

Being based on the given researches the calculations of thermoelastic fields distribution in the sample during of two-beam laser thermosplitting with use of CO_2- and YAG-laser beams with cross-section in the form of a semiring have been executed. Thus, the form and the geometrical sizes of beams are similar to the scheme in Figure 3. The centers of laser beames and a coolant coincide.

Radiation of a CO_2-laser beam with a wavelength λ=10.6 microns, being absorbed in a blanket, realizes the superficial heat of a glass plate. The beam of the continuous YAG-laser with a wavelength λ=1.06 microns, passing through glass volume, fractionally absorbed in it, that leads to volume heat of the sample. Thus, the glass plate is heated by local superficial source of heat in area of CO_2-laser radiation impact and the volume source generated by laser beam with a wavelength 1.06 microns which distribution of intensity in depth follows the Lambert-Buger-Berr law. By means of a power meter IMO-2M measurements of radiation power was done before hitting on a surface of a plate and after passing through the given width plates. Based on the radiation absorption in a material is by the Buger-Lambert-Berr law $I=I_0 \cdot e^{-\alpha z}$ where I_0 – value of intensity of laser radiation before hit on a sample, α – an absorption coefficient, z – the radiation depth of penetration, absorption coefficient recalculation α has been done. It has been received, that α =86.129 m^{-1}. Radiation power of CO_2-laser P=15 W, YAG-laser P=140 W.

In Figure 5 is presented spatial distribution of thermoelastic stresses σ_{yy} arising at realization of the given scheme.

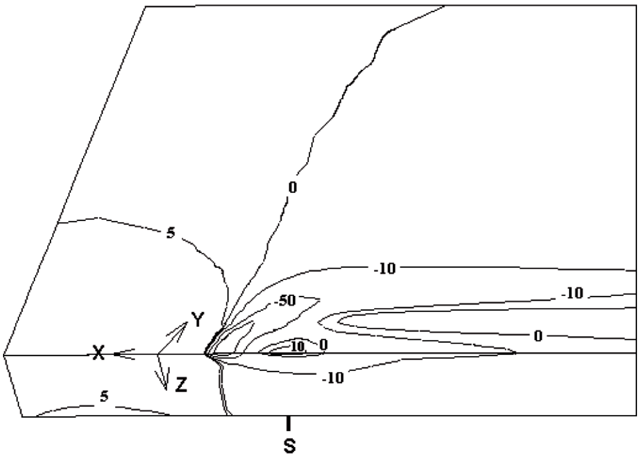

Fig. 5. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample by using of a semiring CO_2- and YAG-laser beams

Apparently from the presented distribution the use of volume source leads to that in the area of coolant giving the zone of tensile stresses is formed, so in each side and below this area is limited by zones of considerable compressing stresses. However the maximum volume of compressing stresses is less than ultimate strength of glass. As a result the crack initiation will not take place.

Thus, for assigned problem realization it is necessary to save the considerable area of a warm-up of a material surface along a treatment line (as the use of elliptic laser beams) and simultaneously additionally warm up the sample in each side of a coolant feeding area for the purpose of forming there the zone of considerable in value compressive stresses that do not allow crack to be deflected near the side boundary of the sample.

For this purpose it is necessary to use a laser beam with a cross-section in the shape of a crescent [13]. The scheme of realization of the given method is presented in Figure 6. The position 1 marks the shape of a laser source spot an a on a material surface, by a position 2 – a coolant. For calculations next parameters of treatment are selected. The internal beam counter corresponds a circle with radius r=1.7 mm, the external beam counter correspond an ellipse with sizes of major and small axes A=10 mm and B=5.4 mm respectively. Laser radiation power P=26 W.

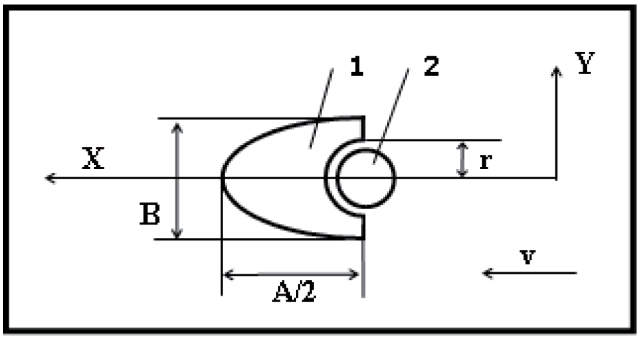

Fig. 6. The layout of a crescent-shaped laser beam and a coolant in a treatment plane

In Figure 7 the spatial distribution of thermoelastic fields σ_{yy} arising at realization of the given scheme is presented. The pattern of fields is presented for half of plate. Position S in figure marks a location of a laser beam center and a coolant along an axis X. Maximum value of temperature in the sample does not exceed 760 K.

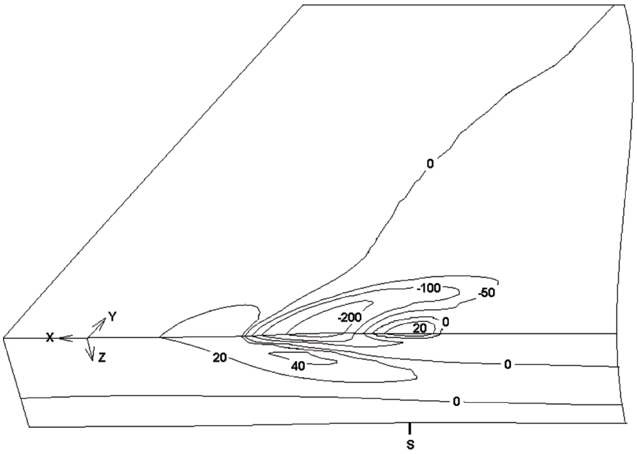

Fig. 7. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample by using of a crescent-shaped laser beam

As it follows from presented distribution, in the field of coolant impact there is a zone of the tensile stresses which value is enough for crack initialization. In front and below it is enveloped by a zone of considerable in value compressive stresses which control development of a crack along a treatment line and in depth. Simultaneously the zone of considerable on value compressive stresses is formed on one side of a coolant feeding area. The given zone allows to control a deviation of a crack from a line along which it is carried on material separations at treatment nearby to side boundary of the sample, i.e allows to block a deviation of a crack towards side boundary in the presence of microdefects and microcracks.

Based on the received results the method of two beam laser thermosplitting with the use of beams CO_2 – and YAG-lasers with a cross-section in the form of a crescent shape is offered. The scheme of realization of the given method is presented in figure 6. Geometrical sizes of cross-sections of beams and also a location of their centers coincide. The internal beam counter represents a circle with radius r=1.7 mm, the external beam counter represents an ellipse with sizes of major and small axes A=10 mm and B=5.4 mm accordingly. Radiation power of CO_2-laser P=18 W, YAG-laser P=140 W.

In Figure 8 the spatial distribution of thermoelastic stresses σ_{yy} arising at realization of the given scheme is presented. The pattern of fields is presented for half of plate. Maximum value of temperature in the sample does not exceed 755K.

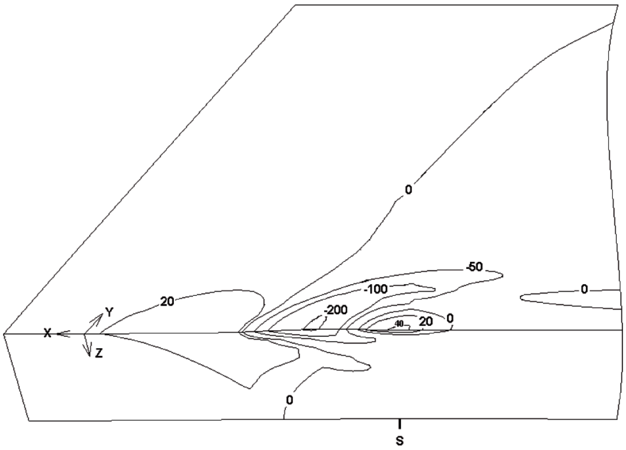

Fig. 8. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample by using of a crescent-shaped CO_2- and YAG-laser beams

From presented distribution it is follows, that as well as in the previous case in front and on one side of a coolant feeding area there is a zone of the strong compressive stresses in consequence of the superficial heat of material by a beam of the CO_2-laser which controls development of a crack along a treatment line of a material (axis X). In the area of coolant impact there is a zone of the tensile stresses, value of which is considerably higher than the only action the CO_2-laser and makes the order 48 MPa. In table 1 calculated values of the maximum temperatures on a surface of material T_{max}, and tensile stresses σ_{yy} in the area of a coolant influence for various schemes of controllable laser thermosplitting process are resulted. Comparing with values of the maximum tensile stresses in the area of coolant influence at realization of all above described schemes presented in table 1, except for the first, at realization of last way they are highest.

In turn it ensures high stability of crack initialization process. In case of two beam treatment, at the expense of a volume absorption radiation of the YAG-laser by material, the field of compressive stresses locates in deeper layers of a material. Below the tensile stresses fields formed in consequence of a coolant impact, the zone

TABLE

Calculated values of the maximum temperatures on a surface of material T_{max}, and tensile stresses σ_{yymax} in the area of a coolant influence for various schemes of controllable laser thermosplitting process

	with the use of elliptic CO_2-lase beam	with the use of semiring CO_2-laser beam	with joint use of semiring CO_2- and YAG- laser beam	with the use of crescent-shaped CO_2-laser beam	with joint use of crescent-shaped CO_2- and YAG- laser beam
Laser beam power, W	30	20	15 (CO_2) 140 (YAG)	26	18 (CO_2) 140 (YAG)
T_{max}, K	747	738	760	760	755
σ_{yymax}, MPa	53	–	15	35	48

of compressive stresses is formed in all material thickness. Such spatial arrangement ensures substantial increasing of depth of a dividing crack in comparison with one-beam treatment (almost twice).

4. Conclusions

Carried out in this paper numerical modelling of process of controllable laser thermosplitting has shown, that the best description while cutting along side boundary of the sample in a small distance from it is the classical scheme of realization of the given method with the use of laser beams with a cross-section of crescent shape. The use of a crescent beam of the CO_2-laser as the technological instrument that allows to form zones of the considerable compressive stresses not only in front and below zones of the tensile stresses generated in the area of a coolant impact, but also in each side from it. The similar spatial distribution allows to control development of a crack not only along a treatment line and in its depth, but also to block its deviation towards the microdefects which are at the edges of the sample. Complementary simultaneous the use of the YAG-laser radiation, the wavelength is corresponded to a volume absorption a processing material, will allow to raise stability of process crack initialization at the expense of substantial increase of values of tensile stresses in the area of coolant action, and also will ensure substantial increase of depth of a dividing crack in comparison with one-beam treatment, at the expense of deeper disposition of a compressive stresses zone restricted below field of tensile stresses.

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