THE ANALYSIS OF LASER THERMOSPLITTING OF MATERIALS BY USING OF CRESCENT-SHAPED BEAMS

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ABSTRACT

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. Modelling is executed for laser beams with a cross-section in the form of an ellipse, a ring, and semi-ring and crescent beams. The classical circuit of realization of the given method consists in the superficial heating of a material by laser beam and the aftercooling of this zone by means of a refrigerating medium. Thus, the microcrack, which is organized in the zone of refrigerating medium supply, follows for a laser beam along a treatment line. On the basis of the analysis of allocation of thermoelastic fields it is displayed, that application of the classical circuit of the given method realization with the use of elliptic and ring-shaped beams possesses a number of the disadvantages, one of which is the quick deflection of a microcrack from a line of influence of a laser beam and refrigerating medium at treatment close to collateral border of the sample. Thus, the microcrack is progressed in a direction to collateral border of the sample. It is displayed, that application of crescent beams allows diminishing degree of effects of treatment line closeness to boundary line of the sample on microcrack development. The positive effect is attained due to forming a compression stress zone not only ahead and under the field of a refrigerating medium effects where the microcrack is initialized and explicated, but also on each side of zone of a refrigerating medium effects, that in its turn does not allow a microcrack to be deflected aside.

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 the given method. The classical scheme of realization of the given method is presented in figure 1 and consists in 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 microcrack which follows a laser beam along a treatment line is organized [1, 2]. Final division is fulfilled by mechanical, thermal or ultrasonic finish chopping.

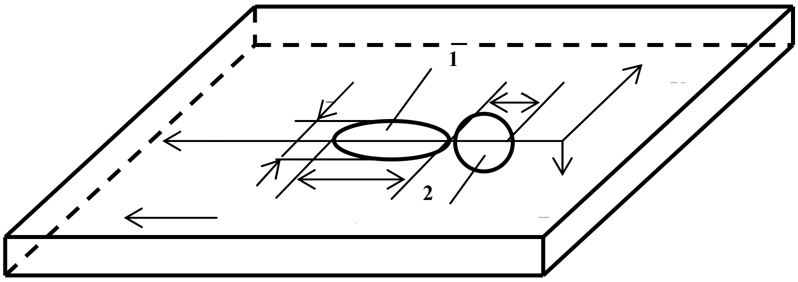

Fig. 1. The layout of an elliptic laser beam and a coolant in a treatment plane

Previously authors had been carried out finite-element solution for 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- laser [5-9] which scheme is presented in figure 1. The problem is solved in quasistatic statement according to [10].

The analysis of allocation of σ_{yy} stress fields has showed, that in a zone of a laser beam impacts considerable on values compressive stresses are formed. In front and in the depth of a material it 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 allocation of thermoelastic fields 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 microcrack 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 from 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 a waste products by manufacture.

According to it searching of 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 a silicate glass with geometrical sizes 40x40 mm and thickness of 3 mm. For calculations it was depends 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, $\alpha=89\cdot10^{-7}$ ($^1/_{°C}$). 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 a 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.

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 on 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 is carried out on 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 accordingly. 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.

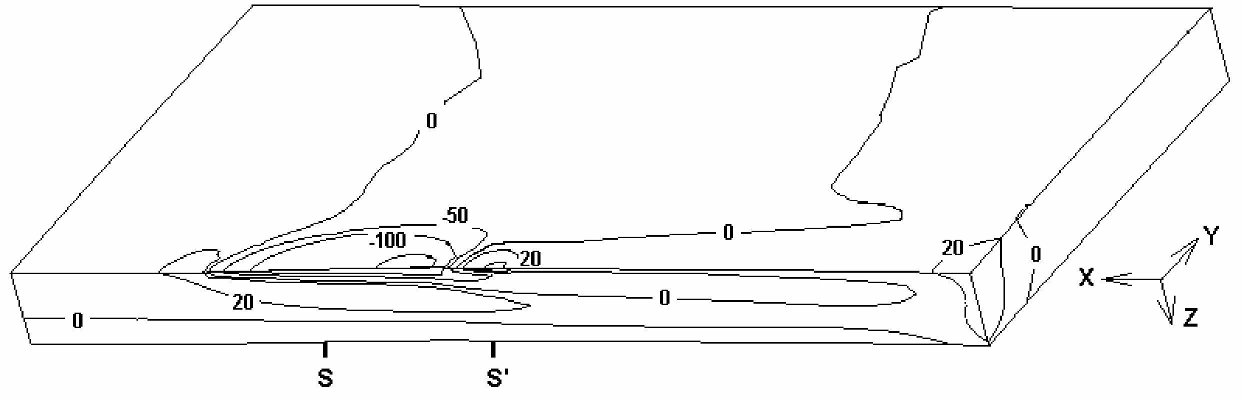

Fig. 2.Distribution of thermoelastic fields σ_{yy} (MPa) in the sample by using of an elliptic laser beam

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. 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. In Figure 3 the spatial distribution of thermoelastic fields is presented to the fixed instant, arising in the process of one-beam laser thermosplitting, when the treatment line (an axis X) is at distance of 3 mm from edge of the sample.

As follows from the received data, the pattern of tensile stress fields in the area of coolant feeding is not symmetrical on both sides from plane Y=0. From side boundary of the sample it is more extended in a direction to it and directly on boundary it positive on values, that it is tensile stresses. Microdefects and microckracks on boundaries of the sample are concentrators of stresses. Therefore at treatment near to side boundary of the sample in apexes of cracks and microdefects zones of considerable on value tensile stresses are formed and the direction of development of the main crack switches towards the given microdefects and microcracks. For removal of the given effect it is reasonable to shape a zone of considerable on value compressive stresses not only in front and below zones of the tensile stresses formed by a coolant, but also on each side from it.

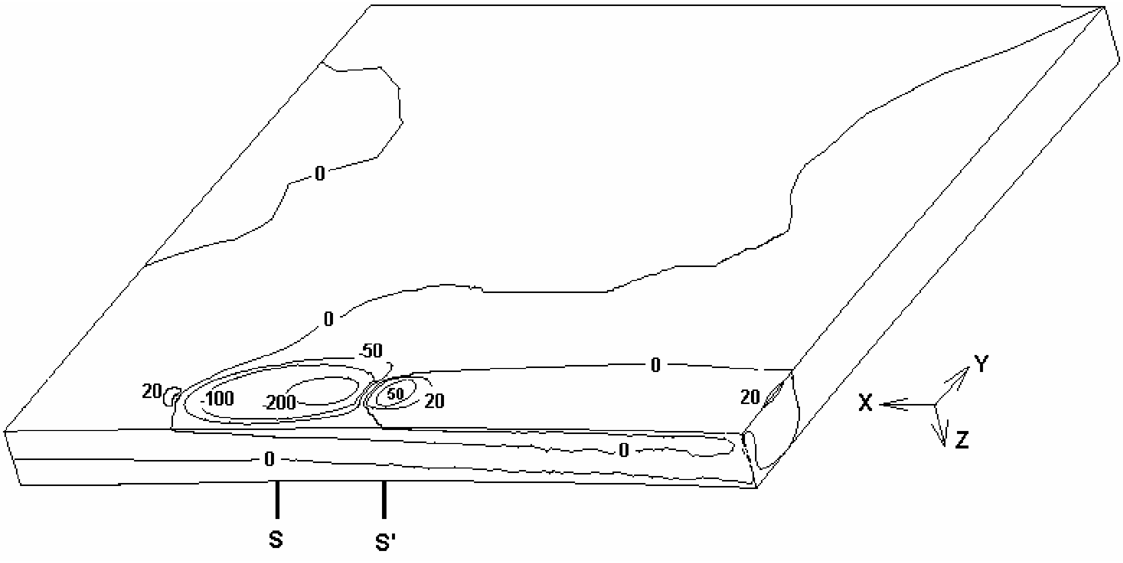

Fig. 3. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample at treatment by an elliptic laser beam on small distances from side boundary

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 4. 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.

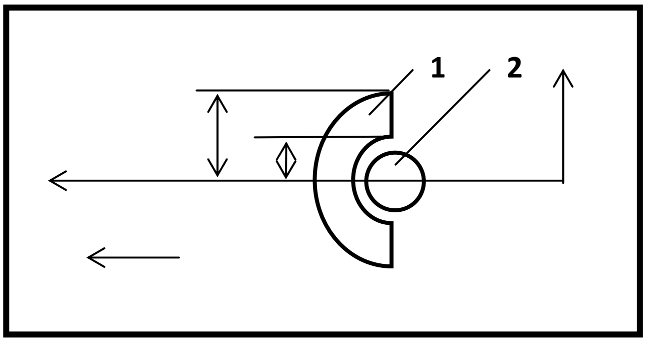

Fig. 4. The layout of a semiring laser beam and a coolant in a treatment plane

In Figure 5 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 centre of a laser bundle and a coolant along an 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 impact of a coolant 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 on 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 that in the area of a coolant feeding stresses σ_{yy} not develops into the tensile.

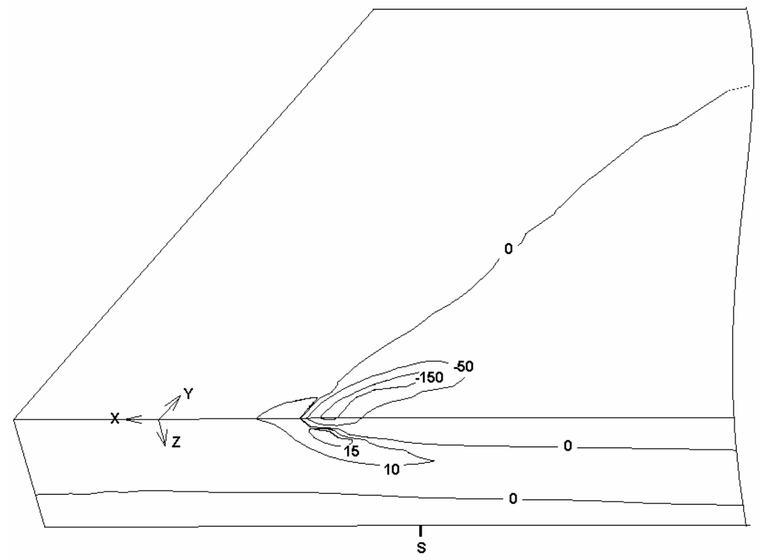

Fig. 5. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample by using of a semiring laser beam

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 at use of elliptic laser beams) and simultaneously additionally warm up the sample on each side of a coolant feeding area for the purpose of forming there zone of considerable on value compressive stresses which are not allow microcrack to be deflected near to 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 of 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 accordingly. Laser radiation power P=26 W.

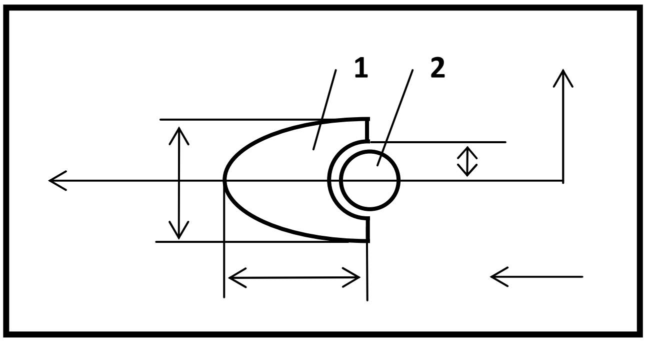

Fig. 6. The layout of a crescent-shaped laser beam and a coolant in a treatment plane

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 centre of a laser beam and a coolant along an axis X. Maximum value of temperature in the sample does not exceed 760 K.

As follows from presented distribution, in the field of coolant impact there is a zone of the tensile stresses which value it is enough for microcrack initialization. In front and below it is enveloped by a zone of considerable on value compressive stresses which control development of a microcrack along a treatment line and on 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 microcrack from a line along which it is carried on material separations at treatment nearby to side boundary of the sample. For the comparative analysis calculation of the elastic stress fields arising in the process of one-beam laser thermosplitting with use of a crescent-shaped beam has been done, when the treatment line (an axis X) is at distance of 3 mm from edge of the sample. From spatial distributions of thermoelastic fields σ_{yy} presented in figure 8 arising at realization of this scheme it is follows, that the zone of tensile stresses formed in the field of a coolant feeding is restricted by a zone of the strong compressive stresses of the order -50 MПa from boundary of the sample, that blocks a deviation of a crack towards side boundary at presence on it microdefects and microcracks.

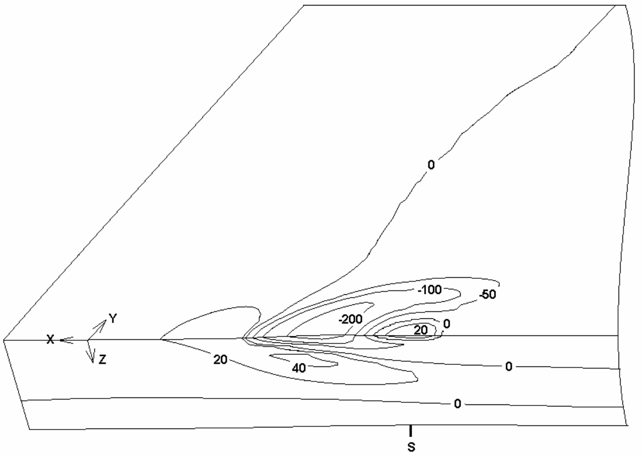

Fig. 7. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample by using of a crescent-shaped laser beam

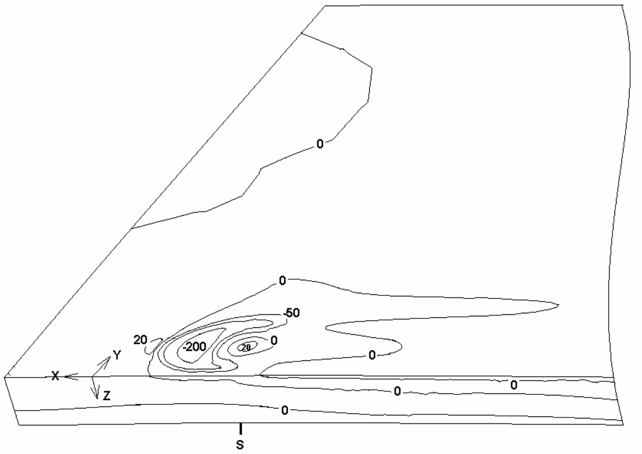

Fig. 8. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample at treatment by a crescent-shaped laser beam on small distances from side boundary

Earlier authors in papers [14-17] had been 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 second corresponds to a volume absorption a processed material. The developed technology of two beam thermosplitting of brittle nonmetallic materials provides a possibility of forming of the given distribution of thermoelastic stresses not only in a thin blanket, but also on all depth of a treatment material. In turn it ensures rising of quality 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.

Based on the received results the method of two beam laser thermosplitting with 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 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 on depth follows to the Lambert-Buger-Berr law. By means of a power meter IMO-2M measurements of radiation power before hit on a surface of a plate and after passing of the given width plates have been done. Based that the absorption of radiation in a material take places under 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, has been done absorption coefficient recalculation α. It has been received, that α =86.129 m^{-1}. Radiation power of CO_2-laser P=18 W, YAG-laser P=140 W.

In figure 9 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. Maximum value of temperature in the sample does not exceed 755K.

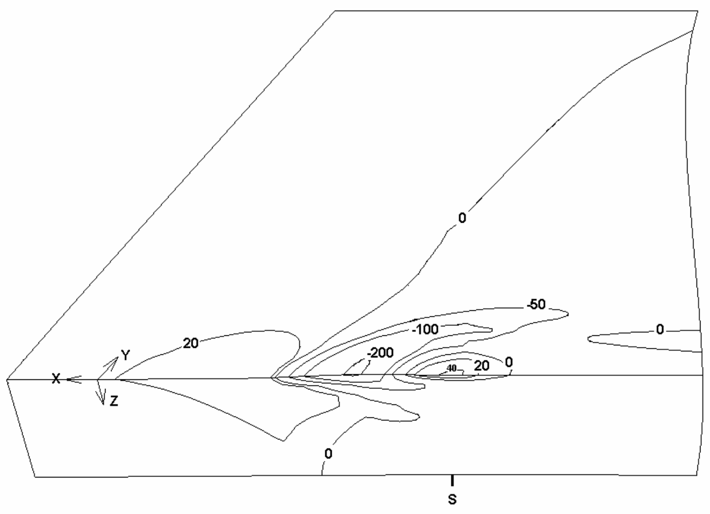

Fig. 9. Distribution of thermoelastic fields σ_{yy} (MPa) in the sample by using of a crescent-shaped CO_2- and YAG-laser beams

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, which value considerably above than in case of action only the CO_2-laser and makes the order 48 MPa. In turn it ensures high stability of process of initialization of a crack. 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 fields of the tensile stresses formed in consequence of a coolant impact, the zone of compressive stresses is formed on all thickness of a material. Such spatial arrangement ensures substantial increasing of depth of a dividing microcrack in comparison with one-beam treatment (almost twice).

4. CONCLUSIONS

The numerical modelling of the process of controllable laser thermosplitting carried out in this paper has shown, that the best description at materials cutting along side boundary of the sample on small distances 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. Use of a crescent beam of the CO_2-laser as the technological instrument allows forming 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 on each side from it. The similar spatial distribution allows one to control development of a crack not only along a treatment line and on its depth, but also to block its deviation towards the microdefects which are at edges of the sample. Complementary simultaneous use of the YAG-laser radiation, which wavelength corresponds to a volume absorption a processing material, will allow to raise stability of process microcrack 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 microcrack 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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