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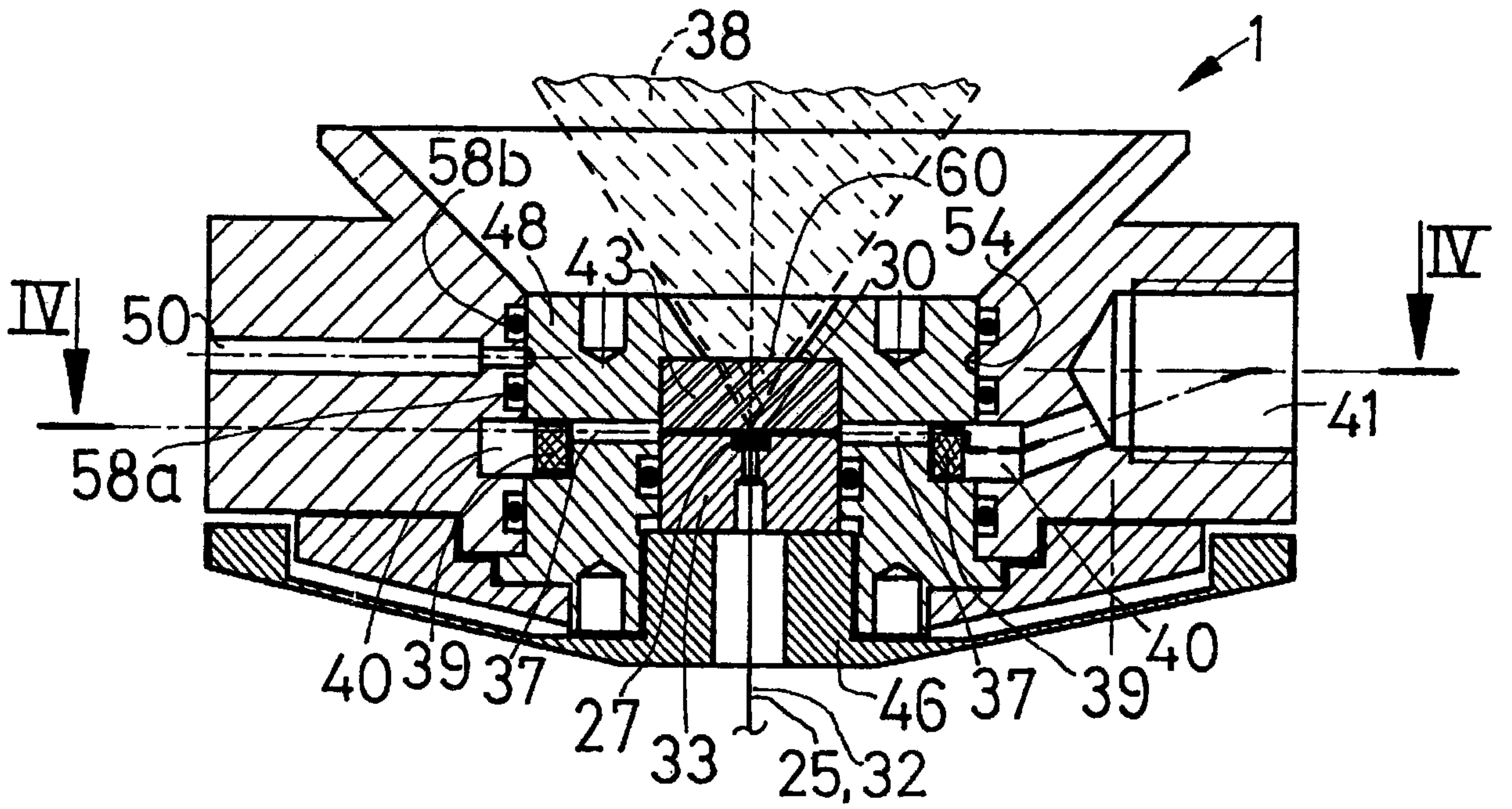
(54) Titre : DISPOSITIF DE FACONNAGE DE MATIERE AVEC UN FAISCEAU LASER INJECTE DANS UN JET DE LIQUIDE

(54) Title: MATERIAL SHAPING DEVICE WITH A LASER BEAM WHICH IS INJECTED INTO A STREAM OF LIQUID



(57) **Abrégé/Abstract:**
The invention relates to a method and device for shaping material of work pieces using a laser beam which is injected into a stream of liquid. The liquid which is to be formed into a stream by a nozzle channel is fed to the nozzle channel opening such that the flow does not swirl, especially without flow components which are tangential to the nozzle channel axis. The laser irradiation is focussed on the channel entry plane and the liquid is fed to the channel opening in such a way that a liquid retention space is avoided in the beam focussing ball and in the immediate surroundings thereof.

ABSTRACT

The invention relates to a method and device for shaping material of work pieces using a laser beam which is injected into a stream of liquid. The liquid which is to be formed into a stream by a nozzle channel is fed to the nozzle channel opening such that the flow does not swirl, especially without flow components which are tangential to the nozzle channel axis. The laser irradiation is focussed on the channel entry plane and the liquid is fed to the channel opening in such a way that a liquid retention space is avoided in the beam focussing ball and in the immediate surroundings thereof.

MATERIAL SHAPING DEVICE WITH A LASER BEAM WHICH IS INJECTED INTO A STREAM OF LIQUID

The invention relates to a method for machining material and to a material-machining device.

Prior Art

Material machining using laser radiation is used in a very wide variety of ways for cutting, boring, welding, marking and generally for removing material. To make it possible to commence removal of material, a predetermined intensity of the radiation has to be reached on the material surface which is to be machined. This high radiation intensity used to be achieved by focusing the laser radiation at the focal point. However, a drawback of this technique is the small axial extent of the focal point (beam width) in which this high intensity was reached. If deep cuts or holes are to be made, the location of the focal point had to be maintained with a very high level of accuracy or even tracked. The beam tapers conically toward the focal point, meaning that particularly in the case of deep cuts, starting on the surface it was always necessary to remove sufficient amounts of material for the conical beam to be able to reach the machining location. However, deep cuts or holes always have to be made with inclined side walls.

To avoid having to track the focal point and to be able to make narrow cuts and holes with approximately vertical side walls, it has been proposed in US-A 5 773 791, EP-A 0 515 983, DE-A 36 43 284 and WO 95/32834, to inject laser radiation into a liquid jet, as a light conductor, which is directed on to the workpiece to be machined.

In DE-A 36 43 284, the laser radiation was supplied by means of a glass fiber. The end of this glass fiber had a water jet which was directed onto the workpiece to be machined flowing around it. The known device had the drawback that the diameter of the water jet was never allowed to be smaller than that in the glass fiber carrying the laser radiation. A further drawback resulted from a region of dead water beneath the end of the glass fiber, causing, among other things, disturbances in the water jet flow and ultimately leading to this jet rapidly breaking down into drops.

EP-A 0 515 983 has attempted to avoid these drawbacks by designing an optics unit with a nozzle block which shapes the water jet. Upstream of the nozzle which shapes the water jet was a water retention chamber having a water inlet and a focusing lens, which closes off the chamber from the nozzle entry, for focusing the laser radiation. The location and focal length of the focusing lens were selected in such a manner that the focal point of the laser radiation was located in the axial center inside the nozzle channel. In operation during machining, it has been found that the nozzle was very quickly damaged by the laser radiation, and consequently the shaping of the radiation was no longer perfect.

An improvement to the way in which the laser beam is injected into the liquid jet was made in WO 95/32834, in which the focal point of the laser radiation to be injected was placed in the plane of the nozzle opening and the water retention chamber in front of the nozzle opening was eliminated. The nozzle which shapes the liquid jet is in this case positioned in a liquid supply space which extends radially with respect to the nozzle axis and into which a plurality of coaxially distributed, axial liquid channels open out. Even with this arrangement, the nozzle was damaged during operation for the machining of material.

Summary of the Invention

It is desirable to provide a method for machining the material and a material-machining device having a laser beam which is injected into a liquid jet, which method and device ensure that material can be machined over a prolonged running time. Interruption in machining is to occur only at predetermined service intervals. It is desirable to reduce the possibility of unforeseeable interruption, in particular caused by damage to the nozzle block which shapes the liquid jet.

According to one aspect of the invention, there is provided a process for machining the material of workpieces using a laser beam having a laser radiation, where the laser beam being injected into a liquid jet, wherein three requirements have to be satisfied together, namely firstly that the laser beam being focused by a radiation-focusing cone onto a channel-entry plane of a nozzle channel which shapes the liquid jet, where the nozzle channel has a nozzle-channel axis and a nozzle-channel opening lying in the channel-entry-plane, secondly that the liquid which is to be shaped into the liquid jet by the nozzle channel be supplied to the nozzle-channel opening without turbulence, and thirdly that the liquid be supplied to the nozzle-channel opening without a tangential flow component with respect to the nozzle-channel axis and with a rapid flow velocity and without liquid retention spaces, into the immediate vicinity of the radiation-focusing cone, as a result of the flow of liquid being divided into a plurality of equal partial flows which flow in radially and are spaced apart at uniform angles.

According to another aspect of the invention, there is provided a material machining device for machining workpieces according to the process described in the above paragraph. The device has a laser radiation source emitting the laser beam and the liquid jet which is shaped by means of the nozzle channel of a nozzle block and into which the laser beam of the laser source is injected and guided by an optical focusing unit, where the nozzle channel has a nozzle channel radius and a nozzle exit, wherein the focusing unit is designed and arranged in such a manner, with respect to the nozzle-channel opening of the nozzle channel, that the focusing unit creates a focusing cone having a focal point of the laser radiation lying in the channel-entry plane of the nozzle-channel opening, and there are a plurality of liquid feed lines, which run radially with respect to the nozzle axis and are spaced apart by equal angles, the plurality of liquid feed lines supplying without any liquid retention spaces the focusing cone of the laser radiation and the region immediately surrounding the focusing cone, where the focusing cone is standing on the channel-entry plane of the nozzle-channel opening, and the plurality of liquid feed lines do not allow any turbulence to occur in the liquid even in the region of the nozzle-channel opening and the nozzle channel.

In an exemplary embodiment, the radiation to be injected into the liquid jet is focused into the nozzle entry plane of the nozzle channel which shapes the liquid, and the liquid is supplied to the nozzle entry flowing at a high velocity (without liquid retention spaces) and without turbulence. These three requirements together may be satisfied by a corresponding design of an optics unit as described below.

Exemplary Embodiments of the Invention

Examples of the process according to the invention and the device according to the invention are explained in more detail below with reference to figures. Further advantages of the invention will emerge from the following descriptive text. In the drawing:

Fig. 1 shows a cross section through an optics unit of the material machining device according to the invention,

Fig. 2 shows a longitudinal section through the optics unit illustrated in Figure 1, with an enlarged view of the liquid feeds to the nozzle block which shapes the liquid jet,

Fig. 3 shows a longitudinal section through the nozzle block which is illustrated in Figure 2 and is held in a nozzle mount,

Fig. 4 shows a cross section on line IV - IV in Figure 2, and

Fig. 5 shows an enlarged view of the illustration in Figure 3, showing in particular the generation and guidance of the liquid jet in the nozzle channel.

The optics unit 1, which is illustrated in cross section in Figure 1, of the material-machining device according to the invention is connected to a laser radiation source 6 by means of a radiation conductor 3 via a radiation conductor connector 5. The radiation source 6 is only diagrammatically illustrated in this figure. It is a high-power laser, such as a Nd:YAG laser. The radiation 7 emerging from the radiation conductor 3 in the connector 5 is collimated by means of a collimator 9 to form a beam 10. The beam 10 is guided to a beam-expanding unit 11. The beam-expanding unit 11 can be used to change, i.e. expand, the diameter of the beam 10 which enters it to that of the beam 13 which emerges from it. A diameter factor of from two to eight is envisaged for the beam expansion. This expanding ratio makes it possible to vary the beam width 15 (diameter of the focal point) of the laser beam 13 which is described below. The beam-expanding factor of the beam expanding unit can be changed by motor means through signals of an adjustment unit which is not shown ("motorized beam expander"). The expanded beam 13 is then deflected through 90° by a deflecting mirror 17 and is diverted onto focusing optics 23 as focusing unit by means of a further deflecting mirror 21 which has an adjustment unit 19. The way in which the adjustment unit 19 operates and is used is described below.

It should be pointed out that the theoretical focal point of the focusing optic 23 does not necessarily have to coincide with the beam width 15 of the focused laser beam 13. A deviation of both locations results from beam divergence of the laser beam 13, which can be influenced, inter alia, by the beam-expanding unit 11.

A nozzle block 27 having a nozzle channel 29 is used to shape a liquid jet 25. The focusing optic 23 and the beam-expanding unit 11 are adjusted or arranged in such a manner that the beam width 15 of the focused beam 13 comes to lie in the nozzle-channel entry plane 30 of the nozzle-channel opening 28. The nozzle-channel entry plane 30 continues on both sides into the surface of the nozzle block 27. Figures 2 to 5 show the area immediately surrounding the entry to the nozzle channel 29 which shapes the liquid jet. Figure 3 shows the nozzle block 27 on an even larger scale than Figure 2. The nozzle channel 29 is of cylindrical design. The nozzle block 27 is made from a material which is transparent to the laser radiation (in this case with a wavelength of 1.06 μm) and is mechanically hard, such as for example quartz. However, since it is extremely small, it may also consist of diamond. Compared to a nozzle block 27 made from quartz, a nozzle block 27 made from diamond has a longer service life, the end of the service life making itself obvious through a liquid jet 25 which breaks up even after a short liquid jet length.

The nozzle block does not necessarily have to consist of a material which is transparent to the laser radiation in order to utilize the conditions of total reflection against the nozzle-channel wall. It may also consist of a material which is not transparent and absorbs radiation, provided that the nozzle-channel wall is provided with a coating which reflects the laser radiation and should be able to resist abrasion from the liquid jet. In the case of a nozzle block material which is not transparent, the nozzle surface should also have a reflective coating (to protect against adjustment errors), and so should the underside of the nozzle block (to protect against radiation which is thrown back onto the workpiece from the workpiece of the cloud of plasma).

The nozzle block 27 illustrated in Figure 3 has a planar surface 30 to which the axis 32 of the nozzle channel 29 runs perpendicular. The edge 31 at the nozzle-channel opening 28 between the surface 30 and the channel wall is of sharp-edged design and preferably has a radius of less than 5 µm. This rounded edge 31 is one of further preconditions, which are described below, for generating a liquid jet 25 of great length. This is because it suppresses the formation of turbulence in the liquid. The nozzle block 27 is inserted into a nozzle mount 33. The transition 34 between nozzle mount 33 and nozzle block 27 is designed in such a manner that there is no step present. A step would likewise generate turbulence in the liquid, and this would propagate into the liquid jet 25 shapeed with the nozzle channel 29. The nozzle block 27 illustrated in Figure 3 has an external diameter of 2 mm and a height of 0.9 mm. A nozzle block of this order of magnitude can be manufactured from a diamond at acceptable cost.

As has already been stated above, the nozzle channel 29 which shapes the liquid jet is of cylindrical design, in this case, for example, with a diameter of 150 µm and a length of approximately 300 µm. The length of the nozzle channel 29 should be no greater than twice the diameter of the nozzle channel. The exit of the nozzle channel 29 is adjoined by a conically expanded opening 26. The cone apex angle is in this case eighty degrees. The inner lateral surface 35 of this cone merges continuously into the nozzle mount 33.

The conical design of the inner lateral surface 35 makes it easier to apply a reflective coating, does not interfere with the liquid jet in any way and, on account of its inclination, intensifies the reflection for any radiation which emerges from the liquid jet 25 on account of mechanical inhomogeneities (shock wave, contaminations which have passed through despite filtering ...). The cone angle is selected to be sufficiently great for radiation which emerges from the liquid jet not to impinge thereon at all or to impinge thereon at only a very shallow angle.

The liquid is supplied to the nozzle channel 29 via a narrow, disk-like inner space 36, the height of which corresponds to approximately half the diameter of the nozzle channel 29. The diameter of the inner space 36 corresponds to the diameter of the nozzle mount 33. Twenty feed lines 37, which are round in cross section and the adjacent side walls of which merge into one another as they enter the inner space 36, open into this inner space 36 in a star-shaped arrangement radially with respect to the axis 32 of the nozzle channel 29. This arrangement of the feed lines 37 promotes turbulence-free (radial) supply of liquid to the nozzle channel 27. A pressure-reducing filter 39 is arranged at the entry side of the feed lines 37. This filter 39 is adjoined by an annular space 40 which is supplied with liquid via a supply line 41. The filter 39 is used to generate a uniform liquid pressure in the twenty feed lines 37, resulting in a symmetrical flow of liquid to the nozzle entry. Since the supply line 41 is on only one side, without filter 39 the feed lines 37 adjacent to the supply line 41 would be at a higher pressure than those lying opposite the supply line. Consequently, it is impossible for tangential flow components to form in the region of the nozzle-channel opening 28. To allow the laser radiation to reach the nozzle-entry opening, the disk-like inner space 36 is covered in a liquid-tight manner by a cover 43 which is transparent to the laser radiation used.

The low height of the inner space 36 provides a high flow velocity of the liquid. Due to the high flow velocity, there is no (or a considerably reduced) possibility of the liquid being heated in the focusing cone 38 by the laser radiation passing through it. On account of the design described above, the disk-like inner space 36 is such that it is impossible, in particular in the radiation-focusing cone 38 of the laser radiation, for a liquid retention space, which would preferentially promote the formation of a thermal lens through radiation absorption, to form. A thermal lens would make perfect, stable focusing of the laser beam into the center (axis 32) of the nozzle-channel opening 28 impossible. The presence of a thermal lens would cause the focusing of the radiation to deteriorate, since the thermal lens acts as a diverging lens. The laser radiation would impinge on the edge of the opening of the nozzle and/or the nozzle surface and would therefore damage the nozzle. Furthermore, the thermal lens formed as a result of the liquid heating would not have a stable location. The radiation would no longer be optimally injected into the liquid jet 25.

On account of the star-shaped (radial) arrangement of the feed 37, a pressure-reducing filter 39 between the entry to the feeds 37 and the annular space 40, a continuous transition 34 in the flow region of the liquid between nozzle block 27 and nozzle mount 33, and the small rounding (radius >5 μm) of the edge 31 where the liquid enters the nozzle, for the first time turbulence-free flow is achieved as a precondition for a liquid jet 25 of great length. Furthermore, degassing of the liquid and removal of particles from the liquid have a positive effect on the production of a great jet length. It should also be ensured that the supply of liquid is free of pressure pulses. This is because the cylindrical shape of the free liquid jet is unstable. On account of its surface tension, the liquid seeks to change into a different shape, namely that of a ball. Therefore, after a certain spreading length, the jet of liquid breaks down into individual drops. An infinitesimally small radial disturbance in the liquid jet during its shaping becomes rapidly more intensive, so that the jet may become constricted, causing it to break up into drops. The air surrounding the jet which is entrained by friction additionally increases this effect. A liquid jet of great length can only be produced by the measures listed above for creating a liquid supply which is free from disturbance.

Furthermore, it has surprisingly been found that, when the liquid jet 25 impinges on an as yet unmachined workpiece surface, a shock wave begins to rise upward in the jet. This shock wave means that the flow of liquid is no longer laminar and some of the laser radiation which has been injected into the liquid jet 25 at the entry to the nozzle opening emerges from the liquid jet 25 on account of irregularities on the lateral surface of the liquid jet caused by the shock wave. This emerging radiation would then come into contact with the nozzle block 27, would pass through the latter and would then be thrown onto the metal wall of the nozzle mount 33. Then, the radiation would be absorbed on this wall causing local heating. This could lead to the material of the nozzle mount 33 melting or vaporizing, which would lead to destruction of the nozzle mount 33 and the nozzle block 27. To prevent this from happening, the inner wall 35 is of conical design and is provided with a reflective coating. The laser radiation emerging on account of irregularities in the lateral surface of the liquid jet is therefore reflected by this coating and cannot penetrate through the nozzle block 27 to the absorbent material. Once the workpiece 45 has been bored or cut through, there are no shock waves or only shock waves with a minimal energy formed.

The nozzle block 27 although having a long life in the arrangement described here, is arranged so that it can easily be exchanged. To exchange the nozzle block, it is merely necessary to unscrew an insert 46.

To check that a seal is produced, the insert 48 accommodating the transparent cover 43 has a groove 54 which runs around its outer lateral surface and opens into a monitoring bore 50. If there is liquid in the monitoring bore 50, the sealing ring 58a has lost its seal. If the sealing ring 58b were then also to lose its seal, liquid could reach the surface 60 of the transparent cover 43, which would considerably impair the focusing and guidance of the laser beam. To avoid this, the sealing rings 58a and 58b are exchanged whenever liquid is registered in the monitoring bore 50.

A force sensor 47 is arranged beneath the workpiece 45 which is to be machined. The position of the force sensor 47 is selected in such a manner that it emits a maximum electrical signal to a control device 49 when the liquid jet 25 is fully impinging on it (without any deflection). The force sensor 47 is arranged in the geometric axis 32 of the liquid jet 25. If the liquid jet 25 with the laser beam which has been injected into it impinges on a workpiece 45 which has not yet been machined, there is no signal, since the jet 25 first has to bore through the workpiece 45. If the workpiece 45 has already been bored through or if there is an initial cut through which the jet 25 is passing, the jet 25 impinges on the slot side wall or bored hole wall when the workpiece 45 is moving. In this case, still only part of the jet 25 impinges on the force sensor 47. The signal emitted to the control device 49 is lower than if the full beam 25 were impinging on it. Therefore, the amount of material which has been removed can be determined by means of the force sensor 47.

The control device 49 is also connected to a displacement device for the workpiece 45. The displacement device is only diagrammatically indicated in Figure 1 by two double arrows in the horizontal directions x and y 51a and 51b, intending to indicate that displacement is possible in one plane and two dimensions. Now, depending on the value determined by the force sensor 47, the control device 49 controls the displacement speed of the workpiece 45 according to a predetermined cutting pattern in the two directions 51a and 51b. The advance of the workpiece 45 which is to be machined can therefore be regulated and optimized in terms of energy by means of the force sensor 47 in that the workpiece 45 is displaced whenever sufficient amounts of material have been removed.

The control device 49 is also connected to the radiation source 6. Therefore, the laser output power can also be adjusted as a function of the measured value from the force sensor and the workpiece displacement velocity. If, in the case of a pulsed laser, by way of example a stepper mode is used for workpiece displacement, the laser emits a plurality of pulses at one location before the workpiece 45 is moved one step onward. The stepper mode may, for example, take place with a step sequence frequency of 100 Hz.

In addition to the guidance of the laser beam which has already been explained above, the optics unit 1, as can be seen from Figure 1, also has means for optimum adjustment and monitoring of the position of the laser beam width (focal point of the radiation), with respect to the nozzle entry opening or the axis 32 of the nozzle channel 29. For this purpose, the radiation 52 from a white light source 53 is superimposed congruently on the expanded laser beam 13. This is carried out by means of the deflecting mirror 17. The deflecting mirror 17 fully reflects the laser radiation but transmits the white light radiation 52 from the white light source 53 behind it. The radiation from the source 53, together with the laser radiation, is guided via the deflecting mirror 21 into the focusing unit 23 and, given correct optical orientation in the nozzle entry plane 30, is focused at the location of the axis 32. The deflecting mirror 21 is designed to partially transmit the white light radiation 52.

To check the correct beam adjustment, only the radiation from the source 53 is used without a laser beam. If there is any incorrect adjustment, the white light radiation which has been focused by means of the focusing unit 23, illuminates the nozzle edge 31 or the area surrounding it. The surface area surrounding the nozzle-entry opening is observed by means of a video camera 55 via a telescope 56 and the deflecting mirror 21, which partially transmits the white light radiation. As it passes through the deflecting mirror 21, on account of the thickness of the latter, the white light undergoes beam displacement. This beam displacement is corrected by a plane-parallel glass sheet 57.

The deflecting mirror 21 can be tilted by an adjustment unit 19. The adjustment elements are then used to tilt the deflecting mirror 21 in such a manner that the focal point of the white light beam comes to lie symmetrically with respect to the location of the channel axis 32.

To achieve this, the procedure is as follows: the deflecting mirror 21 is tilted until radiation reflection can be determined at the nozzle-channel edge 31, and is then tilted in the opposite direction, while measuring the tilting angle (≈ displacement distance of the beam on the nozzle-channel opening) until radiation reflection of the same reflected intensity can also be determined on the opposite nozzle-channel edge 31, and this is followed by a further movement involving tilting back by half the tilting angle. The focal point is then in a plane which includes the nozzle-channel axis 32. For alignment onto the location of the channel axis 32, a further, similar adjustment of the beam axis is then carried out perpendicular to the previous direction of tilting.

The white light source 53 can be dispensed with if the deflecting mirror 21 is made slightly transparent (approximately 2%) for the radiation of the laser source 6. In this case too, the telescope and the glass sheet 57 have to be designed for the laser radiation and provided with an antireflective coating. The video camera 55 must be provided with a chip which is sensitive to the laser radiation. In this case, in the event of incorrect adjustment, the laser radiation is reflected from the nozzle edge or its surrounding region. The reflected radiation is then observed by the video camera 55 via the telescope and an adjustment is performed via the adjustment unit 19 described above and the beam-expanding unit 11. To prevent damage to the nozzle channel and the nozzle surface, the adjustment is carried out with reduced laser power. Since the laser beam properties at high beam intensities may change compared to those at lower power, the adjustment of the deflecting mirror 21 and if appropriate of the beam-expanding unit 11 is commenced with a continuous increase in the laser power.

To check the central setting, the output lens of the beam-expanding unit 11 can then be adjusted in such a manner that the diameter of the beam width of the laser beam 13 is increased until the nozzle-channel edge 31 (i.e. the nozzle-channel opening 28) is uniformly illuminated. Only if illumination is uniform has central alignment been achieved beforehand. The output lens of the beam-expanding unit 11 is then displaced in the opposite direction until uniform illumination of the nozzle-opening edge once again occurs. The position between these two settings then provides optimum focusing onto the nozzle-channel entry plane with the focused beam lying symmetrically with respect to the channel axis 32.

If a Nd:YAG laser is used, the liquid used for the liquid jet may be water. Water exhibits low radiation absorption at 1.06 µm. However, this low absorption may be sufficient for the formation of thermal lenses in front of the nozzle entry. Therefore, for certain applications it is preferable to use a silicone oil in particular selected from the group of polymethylsiloxanes.

If the liquid used is water, the laser radiation used should have an absorption of less than 0.2 cm^{-1} preferably of less than 0.15 cm^{1}. If radiation with higher absorption is used, too much radiation power is aborbed in the liquid jet. High levels of radiation absorption in the liquid may lead to evaporation effects. It is then also impossible, for example, to sufficiently suppress the formation of the thermal lens in the focal point ahead of the nozzle entry even with optimized flow. Low absorption levels with water used as the liquid result at radiations in the wavelength range from 150 nm to 1100 nm, preferably from 190 nm to 920 nm and between 1040 nm and 1080 nm (there is an absorption peak in the range around 1000 nm). Therefore, it is preferably possible to use diode lasers, YAG lasers, frequency-doubled YAG lasers, excimer lasers and copper vapor lasers. A YAG laser has the advantage, for example, that developed, commercially available units are available; they are also able to achieve high mean powers.

The radiation may be continuous or pulsed. In the case of pulsed radiation, the liquid can cool cut edges produced using the process explained above. Heat generated by absorbed radiation in the liquid jet is also dissipated. Therefore, since water has a very high heat absorption capacity, it is possible for high radiation powers to be injected into the liquid jet in pulsed fashion. If a Nd:YAG laser and water as the liquid are used, up to 20 kW pulsed power can be injected with pulse lengths of some 20 to 500 µs, a mean power of 600 W and a pulse rate of up to 5 kHz.

However, it is also possible to use Q-switched Nd:YAG lasers with pulse lengths of typically 50 to 250 ns with a mean power of 20 to 120 W and a pulse rate of up to 60 kHz. It is also possible to use mode-coupled lasers with pulse lengths in the femtosecond range.

Continuously emitting lasers (e.g. cw YAG) can also be used. In this case, however, the mean power is limited by the lack of interruption to the radiation. It is then only possible to inject approximately 700 W radiation power from an Nd:YAG laser into a water jet which is 80 µm thick. At higher laser power densities, the water would be heated to such an extent by the radiation absorption that evaporation would commence beyond a certain jet length. Consequently, the jet would begin to break up into drops; perfect beam guidance would no longer be possible.

The nozzle block 27 described above was produced from quartz or diamond, i.e. from a material which is transparent to the laser radiation. The nozzle exit and the adjoining wall of the nozzle mount 33 were of conical design and were provided with a reflective coating for the laser radiation. It is then also possible to produce the nozzle block 27 from a material which is highly reflective for the laser radiation. For laser radiation of 1.06 µm, it is possible to use a nozzle block made from gold. Since pure gold is too soft, traces of copper and silver have to be added in order to reach a hardness of some 150 to 225 HV.

WHAT IS CLAIMED IS:

1. A process for machining the material of workpieces using a laser beam having a laser radiation, where the laser beam being injected into a liquid jet, wherein three requirements have to be satisfied together, namely firstly that the laser beam being focused by a radiation-focusing cone onto a channel-entry plane of a nozzle channel which shapes the liquid jet, where the nozzle channel has a nozzle-channel axis and a nozzle-channel opening lying in the channel-entry-plane, secondly that the liquid which is to be shaped into the liquid jet by the nozzle channel be supplied to the nozzle-channel opening without turbulence, and thirdly that said liquid be supplied to the nozzle-channel opening without a tangential flow component with respect to the nozzle-channel axis and with a rapid flow velocity and without liquid retention spaces, into the immediate vicinity of the radiation-focusing cone, as a result of the flow of liquid being divided into a plurality of equal partial flows which flow in radially and are spaced apart at uniform angles.

2. Process according to claim 1, wherein the presence of the liquid jet at the location of an extension of the nozzle-channel axis beneath the workpiece is detected, and the workpiece is moved only when this detection occurs.

3. Process according to claim 1, wherein the presence of the liquid jet at the location of an extension of the nozzle-channel axis beneath the workpiece is detected, and the laser power to be injected is changed only when this detection occurs.

4. Process according to any one of the claims 1 to 3, wherein the nozzle-channel opening and a nozzle edge region of the nozzle-channel opening is optically imaged, the beam axis of the laser beam, which is focused onto the channel-entry plane and has an energy which does not remove material, or of an illuminating

beam, which runs congruently with the laser beam, is displaced parallel to the nozzle-channel axis until a radiation reflection can be determined at the nozzle edge region, then the laser beam is moved in the opposite direction, with a displacement distance being measured, until a radiation reflection of the same reflected intensity can be determined at an opposite nozzle-edge region, after which it is once again moved back by half the displacement distance, and then a further, similar adjustment of the laser beam takes place perpendicular to this direction of displacement likewise parallel to the nozzle-channel axis, in order to direct the laser beam centrally onto the nozzle channel which shapes the liquid jet.

5. Process according to any one of the claims 1 to 4, wherein an edge at the nozzle-channel opening between the channel-entry plane and the channel wall is of sharp-edged design and has a radius of less than 5 μm.

6. Process according to any one for the claims 1 to 5, wherein the laser radiation used has an absorption coefficient of less than 0.2 cm^{-1} in the liquid.

7. The process according to claim 6, wherein said absorption coefficient is less than 0.15 cm^{-1}.

8. Material machining device for machining workpieces according to the process of any one of claims 1 to 7, having a laser radiation source emitting said laser beam and said liquid jet which is shaped by means of said nozzle channel of a nozzle block and into which the laser beam of the laser source is injected and guided by an optical focusing unit, where the nozzle channel has a nozzle channel radius and a nozzle exit, wherein the focusing unit is designed and arranged in such a manner, with respect to the nozzle-channel opening of the nozzle channel, that the focusing unit creates a focusing cone having a focal point of the laser radiation

lying in the channel-entry plane of the nozzle-channel opening, and there are a plurality of liquid feed lines, which run radially with respect to the nozzle axis and are spaced apart by equal angles, said plurality of liquid feed lines supplying without any liquid retention spaces the focusing cone of the laser radiation and the region immediately surrounding the focusing cone, where the focusing cone is standing on the channel-entry plane of the nozzle-channel opening, and said plurality of liquid feed lines do not allow any turbulence to occur in the liquid even in the region of the nozzle-channel opening and the nozzle channel.

9. Material-machining device according to claim 8, comprising a disk-like prespace which surrounds the nozzle-channel opening and has said plurality of liquid feed lines having side walls, said plurality of liquid feed lines opening out radially into the prespace, the height of the prespace corresponding to the nozzle-channel radius, in order, so as to avoid a liquid retention space even in the region upstream of the nozzle-channel opening, to have a liquid flow velocity which is only slightly lower than in the nozzle channel, and the side walls of the liquid feed lines, at the location where they open out into the prespace, merge into one another, so that the liquid flowing to the nozzle-channel opening does not acquire any tangential flow components with respect to the nozzle-channel axis.

10. Material-machining device according to claim 8 or claim 9, wherein the liquid feed lines are arranged so as to radiate outwards.

11. Material-machining device according to claim 9 or claim 10, wherein each liquid feed line has an axis, the axes of adjacent liquid feed lines having the same central angle.

12. Material-machining device according to any one of the claims 8 to 11, wherein a length of the nozzle channel is the

shortest possible, and the nozzle channel exit having a conically shaped exit part, the aperture angle of said exit part being larger than a possible partial radiation from the injected laser radiation which may emerge from the liquid jet as a result of any instability.

13. Material-machining device according to claim 12, wherein the length of the nozzle channel is less than four times the nozzle-channel diameter.

14. Material-machining device according to any one of the claims 8 to 13, wherein the laser-beam has a laser radiation with a wavelength in the range from 150 nm to 1100 nm.

15. Material-machining device according to any one of the claims 8 to 14, wherein the laser beam has a laser radiation with a wave-length from 190 nm to 920 nm and 1040 nm to 1080 nm.

16. Material-machining device according to claim 14 or claim 15, wherein the nozzle block is made from quartz.

17. Material-machining device according to claim 14 or claim 15, wherein the nozzle block is made from diamond.

18. Material-machining device according to any one of the claims 8 to 17, wherein the nozzle exit is designed as a cone having a reflective coating for the laser radiation.

19. Material-machining device according to any one of claims 8 to 18, wherein the nozzle block is made from a material which is highly reflective for the laser radiation.

20. Material-machining device according to any one of claims 8 to 19, comprising a force sensor which is arranged as an extension of the nozzle-channel axis beneath the nozzle exit and above

which the workpiece to be machined can be arranged, the sensor being designed in such a manner that, when the liquid jet impinges on it, it emits a signal, so that it is possible to determine when the liquid jet carrying the laser beam has penetrated through the workpiece approximately in the direction of the nozzle-channel axis.

21. Material-machining device according to any one of claims 8 to 20, comprising a liquid-supply control unit which eliminates liquid-pressure pulses in the liquid to be supplied to the nozzle entry, degasses the liquid or removes particles therefrom.

22. Material-machining device according to any one of claims 8 to 21, comprising an observation unit for the nozzle-channel opening and its surrounding area, and an adjustment unit for displacing the focused laser beam which is incident on the nozzle-channel opening in such a manner that it comes to be positioned centrally in the nozzle-channel opening.

23. Material-machining device according to any one of the claims 8 to 22, wherein the liquid is supplied to the nozzle channel via a narrow, disk-like inner space, which is formed between a transparent cover and a nozzle block, said inner space being fed by a star-shaped arrangement of radial feed lines.

24. Material-machining device according to any one of the claims 8 to 23, comprising a pressure-reducing filter between the entry to the feed lines and an outer annular space.

25. Material-machining device according to any one of the claims 8 to 24, wherein the nozzle block is arranged so that it can easily be exchanged by merely unscrewing an insert.

26. Material-machining device according to any one of the claims 8 to 25, comprising a beam expanding unit for expanding the laser beam diameter before being focused by the optical focusing

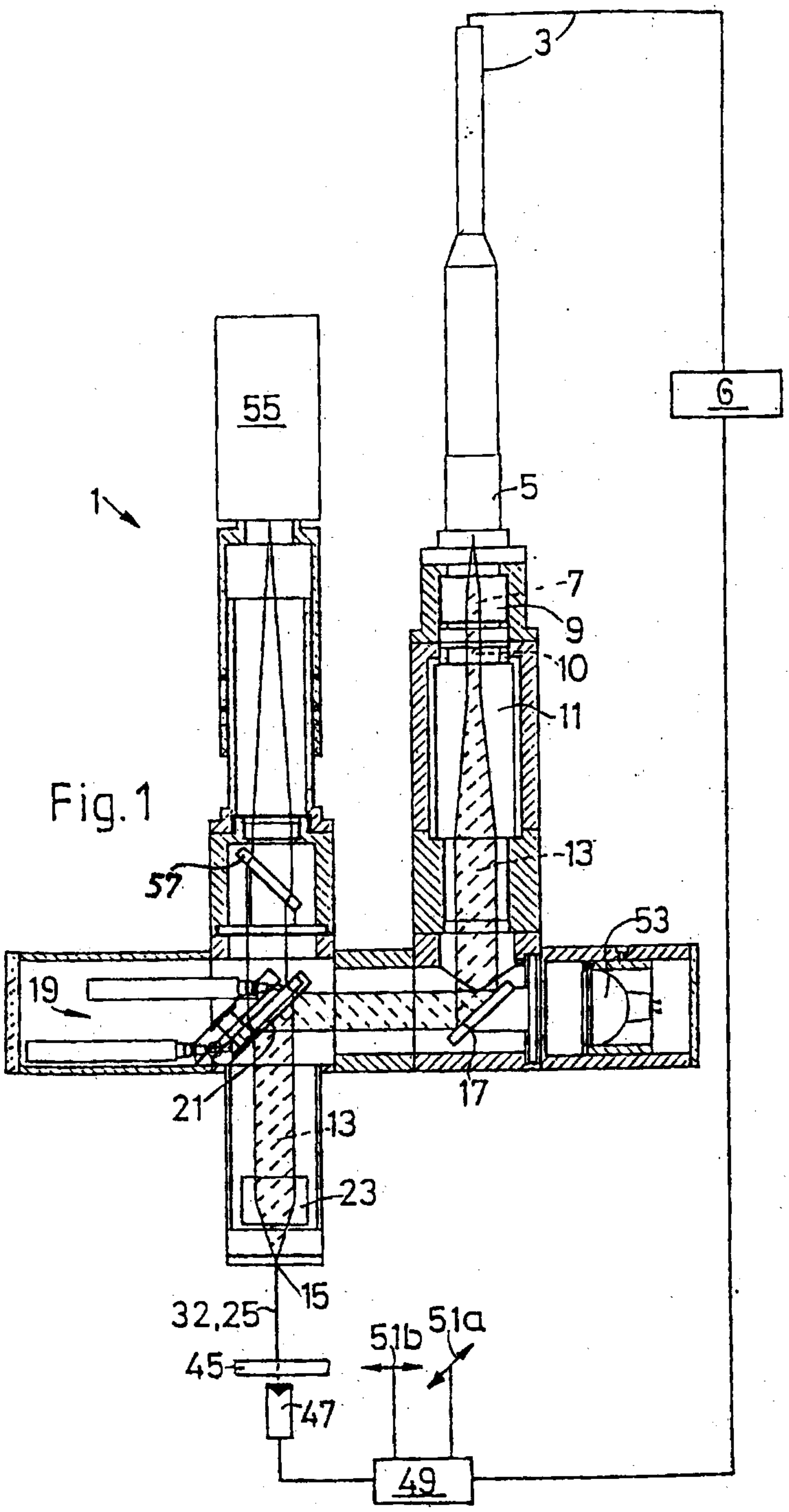
unit, the theoretical focal point of the focusing optic not necessarily having to coincide with the beam width of the focused beam.

27. Material-machining device according to claim 26, comprising:

a wave guide being connected to said laser source, and having at its end opposed to said source a wave guide connector, and

a collimator for collimating said laser radiation emerging from said wave guide connector and guiding said radiation to said beam expander unit.

28. Material-machining device according to claim 23, wherein said transparent cover has a seal check that no liquid could reach the surface of the cover opposite to said inner space.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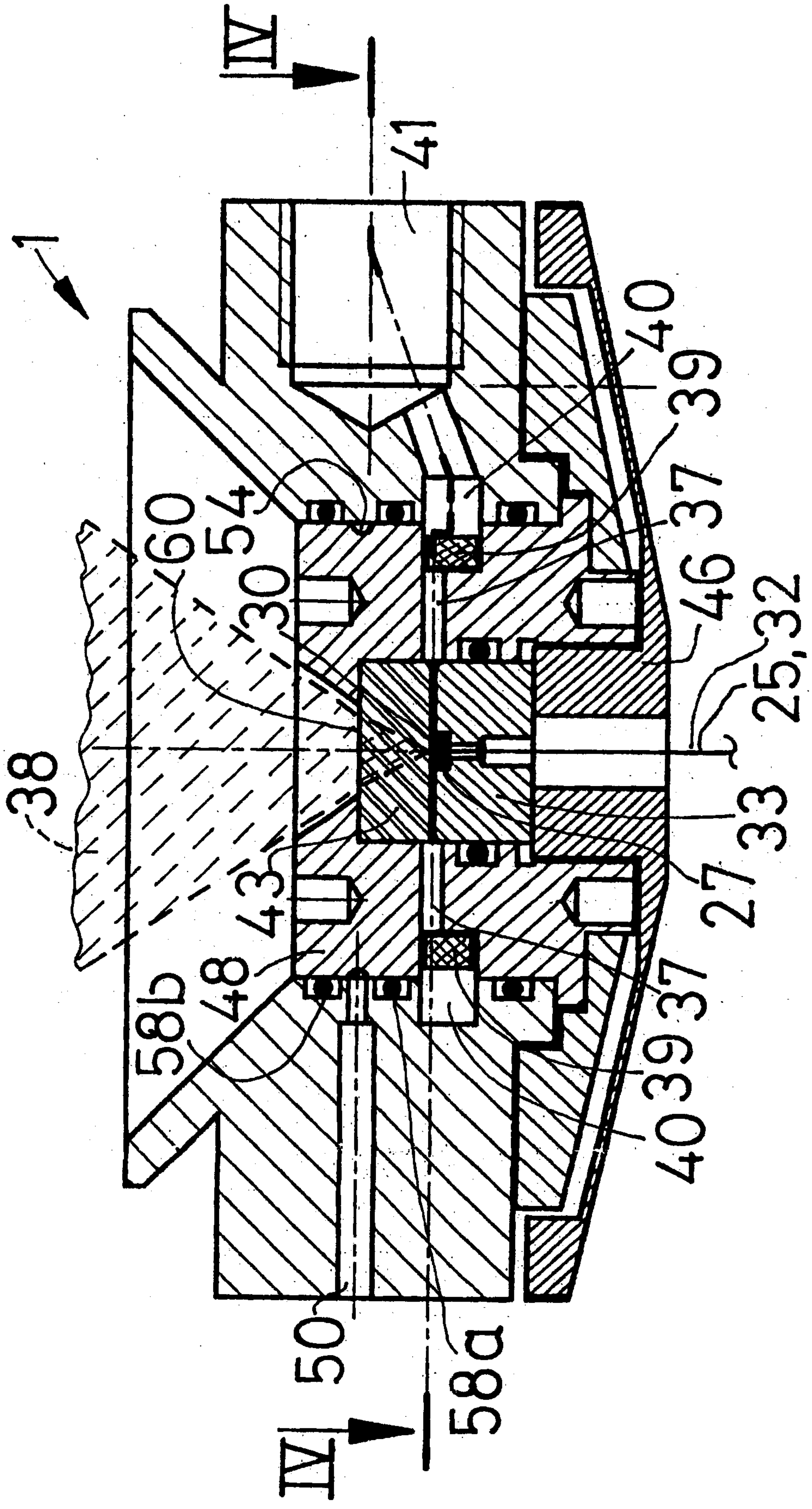

Fig. 2

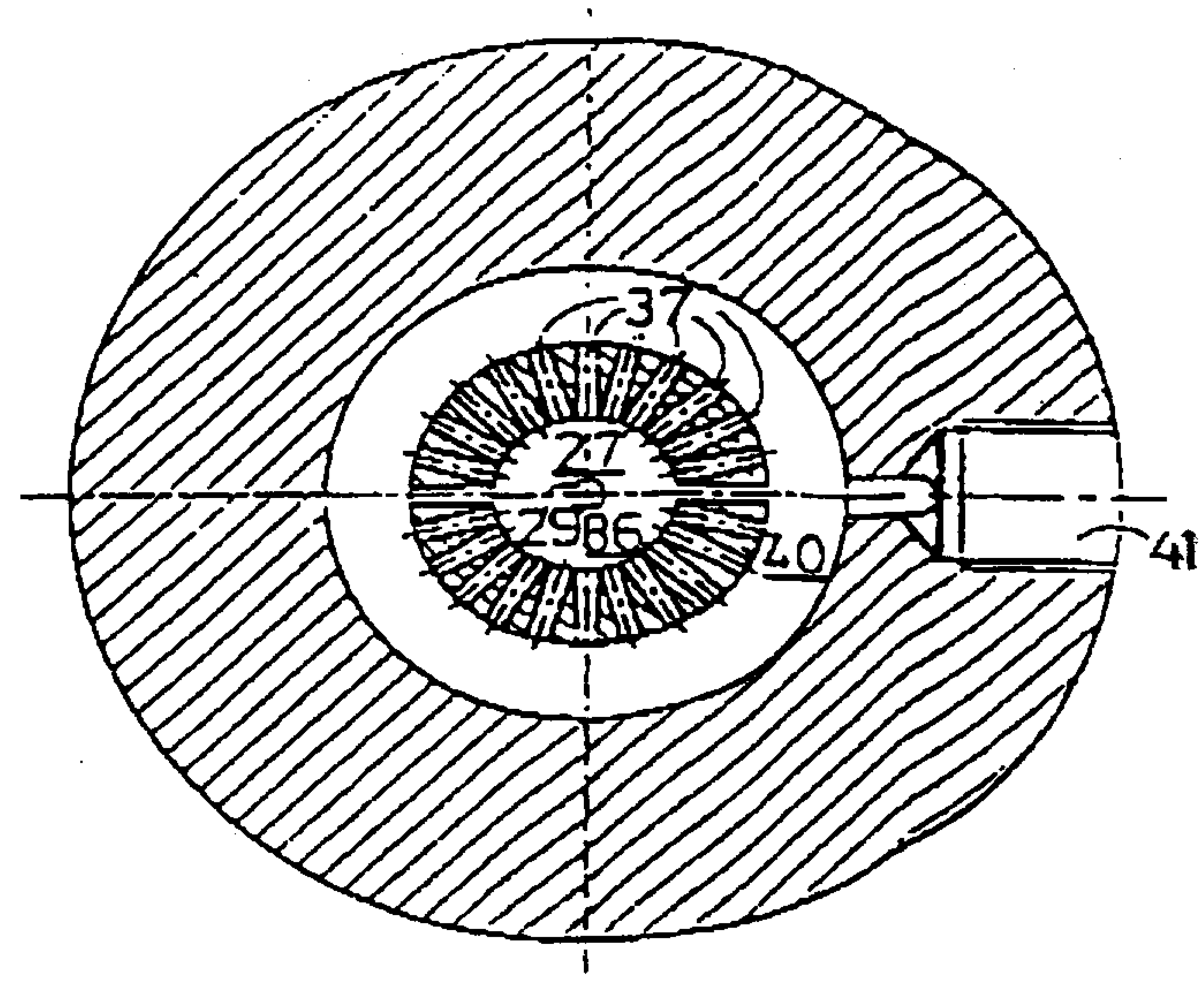

Fig. 4

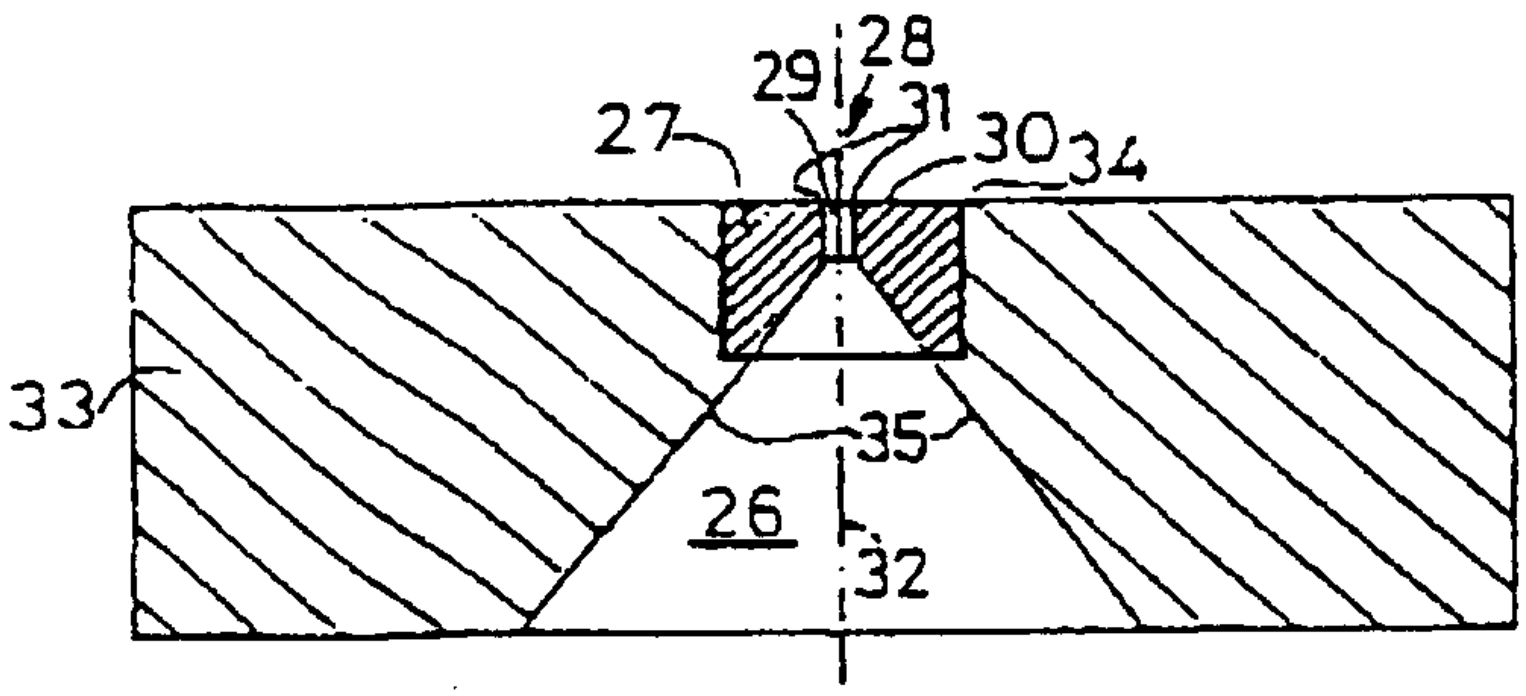

Fig. 3

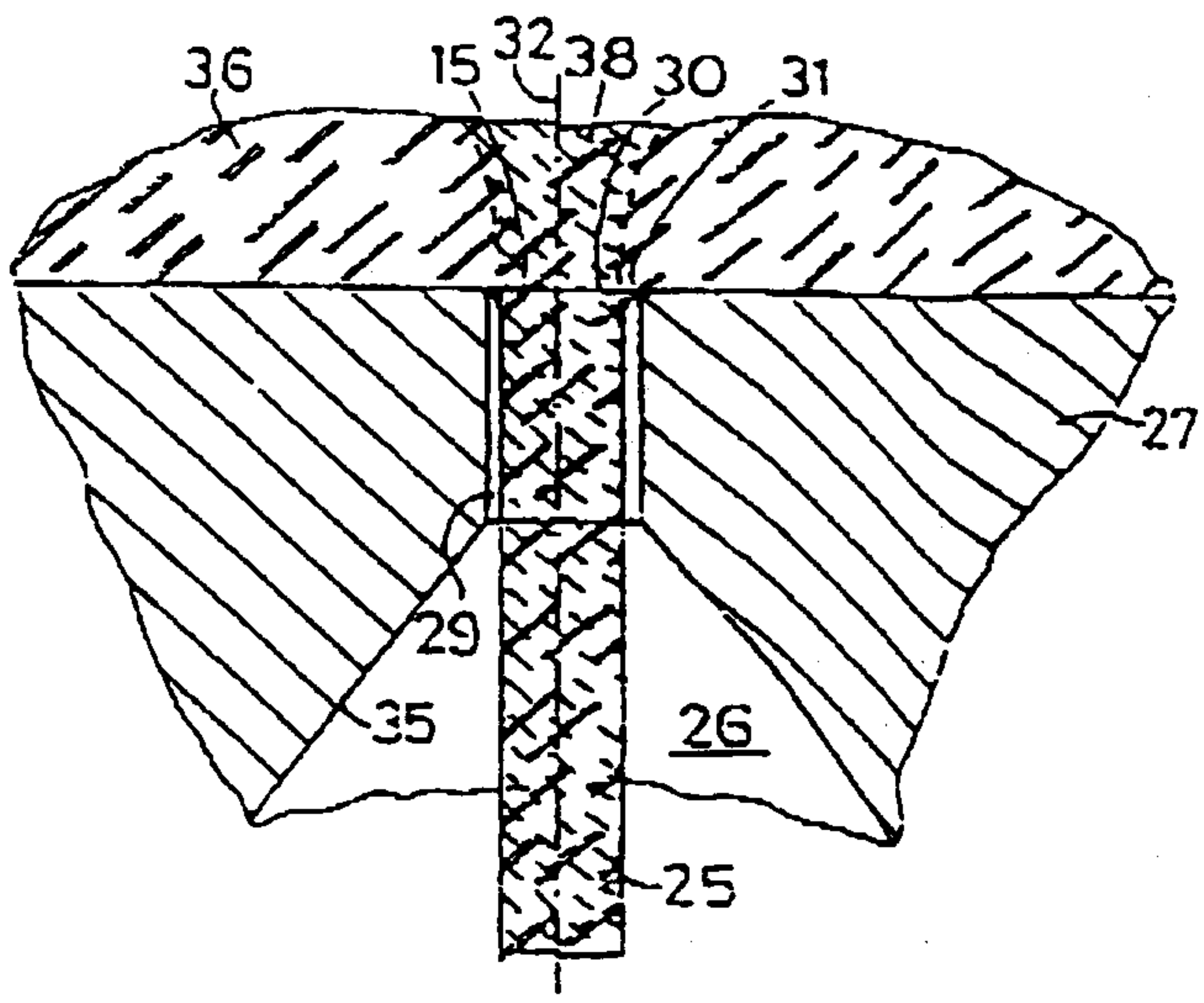

Fig. 5


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58b
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