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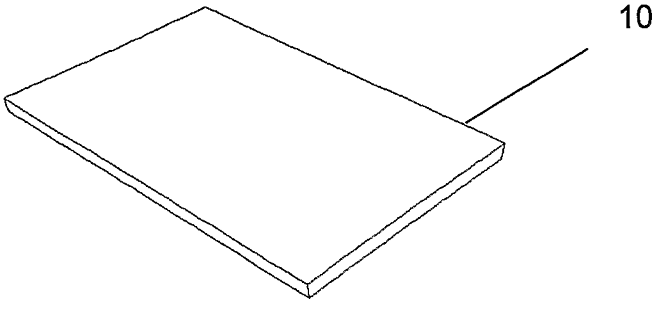

(57) Abstract: An numerical-based technique for designing a process for laser forming of thin plates is described. The method considers the thickness of thin metal plates and determines the values of process variables such as laser power, laser scanning velocity, and laser scanning paths, in order to form a thin metal plate into a desired output curved or multiply-curved three dimensional shape.

A SYSTEM AND METHOD FOR LASER FORMING OF SHEET METAL

SPECIFICATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is based on United States provisional patent application serial no. 60/380,945, filed May 16, 2002, which is incorporated herein by reference for all purposes and from which priority is claimed.

NOTICE OF GOVERNMENT RIGHTS

[0002] The U.S. Government has certain rights in this invention pursuant to the terms of the National Science Foundation award number DMI-0000081.

BACKGROUND OF THE INVENTION

[0003] Technical Field. The present invention relates to techniques for laser forming of sheet metal, in particular for laser forming of three dimensional shapes from thin metal plates.

[0004] Background Art. Conventional sheet metal forming techniques include the use of computer aided design ("CAD") and tooling with a die. A large die, i.e., a mold, may be used to press a flat sheet of metal to form the metal into some three dimensional shape. To ensure that the die is not deformed by the forces employed in pressing the metal sheets, a die is generally composed of a very hard substance.

[0005] Die pressing of sheet metal has several drawbacks. First, the cost of constructing the die itself may be prohibitive in applications where only low volumes of sheet metal are to be pressed. Furthermore, production time for the sheet metal products is lengthened significantly as a result of the additional time required for production of the die itself, which can require two months or more to construct. Moreover, because a die is used for pressing metal and must accordingly be formed out of very hard substances, a die method is not flexible, as the die cannot be easily modified after production begins. In some industries such as shipbuilding, it may not be worth the expense of creating a die, since the product to be formed may only be produced in numbers of tens or hundreds. Furthermore, for applications such as rapid prototyping, a system for metal forming is required which is both fast and flexible, since several iterations of a design will be produced in a short period and often the design is continually modified. Conventional methods cannot meet these requirements.

[0006] More recently, laser forming techniques have provided a more efficient and reliable means for forming sheet metal than were previously available. Laser forming utilizes several process parameters, the most crucial of those being laser power, scanning velocity, and scanning path, to create desired curves in metal sheets. Although process design for laser forming is generally more complex than those for machining, rolling, and die stamping, laser forming for simple three-dimensional shapes can be simple. An empirical-based (trial and error) method may be sufficient where, for example, the goal is to bend a circular flat metal plate into a semispherical shape. However, when more complex three-dimensional shapes are required (e.g., saddle, pillow), it can become substantially more difficult to determine the process parameter values that will produce a desired resulting shape. Laser scanning paths, scanning velocities, and powers must be calculated with precision, and the relationship between heating and deformation can become even more complex. For these more complex shapes, process parameters may no longer be determined empirically.

[0007] There have been numerous efforts toward the analysis and prediction of laser forming ("LF") processes of sheet metal. For example, in a series of articles by Ueda et al. entitled "Development of computer-aided process planning system for plate bending by line heating," 10 J. Ship Prod., 59-67 (1994), and 10 J. Ship Prod., 239-257 (1994), the use of a "line heating" technique rather than a technique based solely on laser forming is described. However, the process is performed by hand, and therefore is heavily reliant on the skill of a worker and is relatively imprecise.

[0008] In an article by Jang et al. entitled "An algorithm to determine heating lines for plate forming by line heading method," 14 J. Ship Prod., 238-245 (1998) the authors describe an approach for determining heating paths. However, the method contains many empirical factors. Jang et al.'s reliance on known variables reduces the analytical nature of the method, making it less advantageous for production of complex shapes in metal forming.

[0009] Shimizu describes a method for using generic algorithms ("GA") and discrete values for process parameters such as laser power (e.g., where the only available values for laser power are 200W, 400W, 600W). Shimizu et al., "A heating process algorithm for metal forming by moving a heat source," M.S. Thesis, MIT (1997). However, the assumptions made by Shimizu et al. are rather restrictive and result in inflexible solutions. Experimental validation also proved to be a difficult obstacle to the techniques described therein.

[0010] Yu et al. also attempted to develop a method for design of three dimensional curved surfaces. Yu et al., "Optimal development of doubly curved surfaces," 17 Computer Aided Geometric Design, 545-577 (2000). Yu's method also has several limitations. First, the method described cannot handle process many variables, and therefore must provide sample values for some variables. As with Jang et al., this reduces the analytical nature of the method. Additionally no scanning paths are determined in the method described by Yu et al. – instead they are prescribed. Yu et al. also did not provide methods for determining the laser scanning velocity and power, and the results were not validated through experiments.

[0011] Yu et al. determined the elongation/compression at each point (i.e., a "strain field") which is required to deform the flat sheet to yield the final desired three dimensional shape. However, the method described in Yu only dealt with a *surface* which has no thickness – the primary concern being shape or geometry considerations. This reliance on a two-dimensional geometrical method based on differential geometry ignores the thickness of the metal sheets, detracting from the accuracy of the method.

[0012] Accordingly, there exists a need for an analytical process design technique for laser forming of thin metal plates. The technique should be highly analytical, and account for thickness in the sheet metal or metal plates.

SUMMARY OF THE INVENTION

[0013] Accordingly, it is an object of the present invention to fulfill a need in the field of laser forming process design by providing an numerical-based process design technique for laser forming of thin plates.

[0014] Another object of the present invention is to provide techniques which are adapted to determine the values of primary process variables, e.g., scanning path, laser power, and laser scanning velocity, which are necessary to form a particular curved shape from a thin metal plate.

[0015] Another object of the present invention is to provide techniques which are adapted to achieve a high degree of accuracy by considering the thickness of the metal plates.

[0016] In order to meet these and other objects of the present invention which will become apparent with reference to further disclosure set forth below, the present invention provides numerical process design techniques for laser forming of thin metal plates. One exemplary method comprises the steps of receiving a thin plate having a curved shape, determining a strain field corresponding to the desired curved shape with a large-deformation elastic finite element technique, determining a minimal principle in-plane strain for each point of the strain field, and determining a scanning path related to the direction of the minimal principal in-plane strain for one or more points of the strain field.

[0017] Additional steps in other exemplary embodiments of the present invention may include determining the laser power and scanning velocities for the various scanning paths.

[0018] Advantageously, the present invention provides an accurate numerical technique for designing process for laser forming of thin metal plates, which technique accounts for thickness of the thin plates.

[0019] The accompanying drawings, which are incorporated and constitute part of this disclosure, illustrate preferred embodiments of the invention and serve to explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] Fig. 1 is an illustrative diagram showing an exemplary thin metal plate which may be laser formed in accordance with the present invention;

[0021] Fig. 2 is an illustrative diagram showing an exemplary "pillow shape" which may be created from a thin metal plate by laser forming in accordance with the present invention;

[0022] Fig. 3 is an illustrative diagram showing an exemplary "saddle shape" which may be created from a thin metal plate by laser forming in accordance with the present invention;

[0023] Fig. 4 is a flow chart showing the steps in a method according to an exemplary embodiment of the present invention;

[0024] Fig. 5 is an illustrative diagram showing an exemplary method for determining a strain field in accordance with the present invention;

[0025] Fig. 6 is an illustrative diagram showing an exemplary strain field as may be determined in accordance with the present invention;

[0026] Fig. 7 is an illustrative diagram showing an exemplary strain field with an overlay of exemplary laser scanning paths as may be determined in accordance with the present invention;

[0027] Fig. 8 is a three-dimensional graph which may be used in accordance with the present invention;

[0028] Fig. 9 is an illustrative diagram showing an exemplary embodiment of a portion of a strain field with corresponding segments as may be used in accordance with the present invention; and

[0029] Fig. 10 is a functional diagram of an exemplary system in accordance with the present invention.

[0030] Throughout the Figs., the same reference numerals and characters, unless otherwise stated, are used to denote like features, elements, components or portions of the illustrated embodiments. Moreover, while the present invention will now be described in detail with reference to the Figs., it is done so in connection with the illustrative embodiments.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0031] Referring to Figs. 1-3, an exemplary metal sheet or thin plate which may be processed according to the present invention, and two exemplary resulting curved shapes are shown. In particular, Fig. 1 illustrates a sample flat thin metal plate or sheet 10 which may be processed according to the present invention to yield a curved three-dimensional shape. Fig. 2 shows a pillow shape 20 which may be created from the metal plate 10 in accordance with the present invention. Fig. 3 shows a saddle shape 30 which may be created from the metal plate 10 in accordance with the present invention. While the following exemplary description of the invention will be with respect to these so-called pillow and saddle shapes as examples, those skilled in the art will appreciate that the present invention is more broadly applicable to processing thin metal plates or sheets to produce an unlimited number of three-dimensional singly- or multiply-curved shapes. Moreover, a wide variety of different materials may be processed in connection with the present invention. For example, the present invention may be used in connection with processing of metals such as ow carbon steels. This techniques of the present invention may preferably be used to process thin plates (i.e., with aspect ratio: edge thickness < 80:1) because in-plane strain dominates in sheet metal bending. However, the present invention may also be used for thick plates where bending strain and in-plane strain are both significant.

[0032] In accordance with the present invention, Fig. 4 illustrates the steps of an exemplary embodiment of a method according to the present invention for process design of laser forming of thin metal plates. First, a desired curved shape is input in step 41. Next, a strain field is determined in step 42. A minimal principle in-plane strain at each point of the strain field is determined in step 43. A scanning path is determined in step 44, the average power required for each scanning path is determined in step 45, and the laser power for each scanning path is determined in step 46. Next, each scanning path is divided into segments with substantially equal minimal principle in-plane strain in step 47, and finally the laser scanning velocity for each segment is determined in step 48. Each of these steps will be discussed in further detail below.

[0033] More specifically, as indicated in the flow chart of Fig. 4, the first step 41 is to receive a desired curved shape, which may be represented in a computer-aided design ("CAD") format or some other format capable of modeling a three-dimensional object digitally. The next step 42 is to determine the strain field required to develop a desired shape to a planar shape. One method for determining the strain field is, via computer modeling, to place a desired shape between two rigid flat bodies and compress it to a planar shape, as illustrated in Fig. 5. Referring to Fig. 5, rigid body 50 will be given incremental displacements towards the other rigid body 51, along the z direction, modeling the compression of the curved thin plate 52 between the rigid bodies 50 and 51. This may continue until the gap between the two rigid bodies is equal to the thickness of the curved plate 52 and the curved plat has been deformed to be essentially a flat thin plate. The strain field that is required for such a planar development may be solved by finite element method ("FEM"), a technique which is well known to those skilled in the art (e.g., see http://www.finite-element-method.info/).

[0034] In an exemplary embodiment, one type of FEM that may be employed in the determination of the strain field is large-deformation elastic FEM. The reason for using large-deformation FEM is as follows. When the deflection (the normal component of the displacement vector), w_0, of the midplane is small compared with the plate thickness, h ($w_0 \leq 0.2h$), Kirchhoff's linear plate bending theory, a theory which is well known to those skilled in the art, gives sufficiently accurate results. The in-plane strain and the corresponding in-plane stress may be ignored as negligible. However, if the magnitude of deflection increases beyond a certain level ($w_0 \geq 0.3h$), these deflections are accompanied by stretching of the mid-plane. As the ratio w_0/h further increases, the role of in-plane strain becomes more pronounced. Where w_0/h reaches *a* sufficiently high value, the nonlinear effects may beneficially be considered in order to improve the accuracy of the result. Elastic FEM may be beneficial over elasto-plastic FEM because the strain field development from the desired shape to a planar shape is purely geometrical, and should be independent of material properties including both elastic and plastic properties. Using elastic FEM requires only elastic properties such as Young's modulus E to be specified. Furthermore the strain field determination may be independent of the value of E.

Notably, one skilled in the art will realize that there are various different methods of FEM which may be employed to determine the strain field within the scope of the present invention.

[0035] The FEM analysis in an exemplary embodiment of the present invention may be performed as follows. For thin plate deformation, deflection *w(x,y)* may be assumed to be equal to the deflection of the midplane, $w_0(x,y)$. The total strains of deflection can be expressed as follows.

$$\varepsilon_{xx} = \varepsilon_{xx}^0 + \varepsilon_{xx}^1 = [\frac{\partial u_0}{\partial x} + \frac{1}{2}\left(\frac{\partial w_0}{\partial x}\right)^2] + [-z\frac{\partial^2 w_0}{\partial x^2}]$$

$$\varepsilon_{yy} = \varepsilon_{yy}^0 + \varepsilon_{yy}^1 = [\frac{\partial v_0}{\partial y} + \frac{1}{2}\left(\frac{\partial w_0}{\partial y}\right)^2] + [-z\frac{\partial^2 w_0}{\partial y^2}]$$

$$\gamma_{xy} = \gamma_{xy}^0 + \gamma_{xy}^1 = [\frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x} + \frac{\partial w_0}{\partial x}\frac{\partial w_0}{\partial y}] + [-2z\frac{\partial^2 w_0}{\partial x \partial y}] \qquad (1)$$

where u_0, v_0, and w_0 are the displacement at midplane, ε_{xx}, ε_{yy}, and γ_{xy} are total strains, and $\varepsilon_{xx}^0, \varepsilon_{yy}^0$, and γ_{xy}^0 are in-plane strains, and $\varepsilon_{xx}^1, \varepsilon_{yy}^1$, and γ_{xy}^1 are bending strains.

[0036] For small deflection of thin plates, it is assumed that u_0 and v_0 are zero and slopes $\frac{\partial w_0}{\partial x}$ and $\frac{\partial w_0}{\partial y}$ are small. Therefore, the in-plane strains $\varepsilon_{xx}^0, \varepsilon_{yy}^0$, and γ_{xy}^0 are zero and the total strains only contain the bending strains. The bending strains equal to product of position in the thickness direction *z* and a term which approximately equals to the curvature at that point, that is,

$$\varepsilon_{xx} = \varepsilon_{xx}^1 = -z\frac{\partial^2 w_0}{\partial x^2} = zR_x$$

$$\varepsilon_{yy} = \varepsilon_{yy}^1 = -z\frac{\partial^2 w_0}{\partial y^2} = zR_y$$

$$\gamma_{xy} = \gamma_{xy}^1 = -2z\frac{\partial^2 w_0}{\partial x \partial y} = -2zR_{xy} \qquad (2)$$

where, R_x and R_y are approximately the curvature along the *x*-axis and *y*-axis, respectively. R_{xy} can be defined as a twisting curvature, which represents the warping of the *x-y* plane. Given a desired shape, R_x, R_y and R_{xy} are known and therefore the total strains may only depend on z, independent of any material properties. They can be determined independent of Young's modulus in the large-deformation elastic FEM.

[0037] For large deflection of thin plates, the bending strains are the same as in Eq. (2) and the in-plane strains, $\varepsilon_{xx}^0, \varepsilon_{yy}^0$, and γ_{xy}^0 can be expressed by Hooke's law as

$$\varepsilon_{xx}^0 = \frac{1}{h}\left(\frac{\partial^2 \varphi}{\partial y^2} - \nu \frac{\partial^2 \varphi}{\partial x^2}\right)$$

$$\varepsilon_{yy}^0 = \frac{1}{h}\left(\frac{\partial^2 \varphi}{\partial x^2} - \nu \frac{\partial^2 \varphi}{\partial y^2}\right)$$

$$\gamma_{xy}^0 = -\frac{2(1+\nu)}{h}\frac{\partial^2 \varphi}{\partial x \partial y} \tag{3}$$

where φ is stress function ϕ divided by Young's modules E, h is plate thickness, and ν is the Poisson ratio variable.

[0038] φ can be calculated by solving the following governing equations for thin plate deflection under appropriate boundary conditions.

$$\frac{\partial^4 \varphi}{\partial x^4} + 2\frac{\partial^4 \varphi}{\partial x^2 \partial y^2} + \frac{\partial^4 \varphi}{\partial y^4} = h\left[\left(\frac{\partial^2 w_0}{\partial x \partial y}\right)^2 - \frac{\partial^2 w_0}{\partial x^2}\frac{\partial^2 w_0}{\partial y^2}\right]$$

$$\frac{\partial^4 w_0}{\partial x^4} + 2\frac{\partial^4 w_0}{\partial x^2 \partial y^2} + \frac{\partial^4 w_0}{\partial y^4} = \frac{1}{D'}\left[P' + \frac{\partial^2 \varphi}{\partial y^2}\frac{\partial^2 w_0}{\partial x^2} + \frac{\partial^2 \varphi}{\partial x^2}\frac{\partial^2 w_0}{\partial y^2} - 2\frac{\partial^2 \varphi}{\partial x \partial y}\frac{\partial^2 w_0}{\partial x \partial y}\right] \tag{4}$$

where $D' = \frac{h^3}{12(1-\nu^2)}$ is flexural rigidity D divided by E, and $P'(x,y)$ is lateral load in z direction $P(x,y)$ divided by E. As shown by equations (3) and (4), once a desired shape is given, that is, deflection w_0, and curvatures $\frac{\partial^2 w_0}{\partial x^2}$, $\frac{\partial^2 w_0}{\partial y^2}$, and $\frac{\partial^2 w_0}{\partial x \partial y}$ are known, φ and P' and in turn the in-plane strains $\varepsilon_{xx}^0, \varepsilon_{yy}^0$, and γ_{xy}^0 can be calculated under appropriate boundary conditions and the calculation is independent of Young's modulus. As seen in equation (3), they do depend on the Poisson ratio, which is geometrical property.

[0039] As demonstrated above, given a desired shape of thin plate, a strain field required to develop the shape to a planar shape may be determined independent of any material properties, including Young's modules, regardless of the amount of deformation required. The large-deformation elastic FEM may be performed using commercial software tools such as ABAQUS. One skilled in the art will understand that the FEM analysis described in this exemplary embodiment may be accomplished using a plurality of other software tools.

[0040] In laser forming process design, however, it may be difficult to duplicate the strain field with exactitude since laser forming only affects a certain strain distribution. However, it is known that doubly curved shapes can be developed by in-plane and bending strains and laser forming generally yields in-plane and bending strains. As a result, in an exemplary embodiment of the present invention, the total strains ε_{ij} obtained via FEM may be decomposed into in-plane strain ε_{ij}^{1}, and bending strain, ε_{ij}^{0}, as follows.

$$\varepsilon_{ij}^{0} = \frac{1}{h}\int_{-\frac{h}{2}}^{\frac{h}{2}} \varepsilon_{ij} dz$$

$$\varepsilon_{ij}^{1} = \frac{2}{h^2}\int_{-\frac{h}{2}}^{\frac{h}{2}} z(\varepsilon_{ij} - \varepsilon_{ij}^{0}) dz \qquad (5)$$

[0041] In this embodiment, the in-plane strain arises from the integration of the total strain along thickness *h*. For thin plates, however, the in-plane strain equals the midplane strain because the bending strain varies linearly with *z* as seen from equation (1) and $w(x,y,z)=w_o(x,y)$.

[0042] After a strain field is determined and decomposed into in-plane and bending strain components, referring back to Fig. 4, the next step 43 in an exemplary method according to the present invention is to find the direction and magnitude of minimal principal (compressive) strain for both, in order to determine laser scanning paths. It is well known that under the temperature gradient mechanism, highest compressive strains occur in the direction perpendicular to a laser scanning path. Therefore, in an exemplary embodiment of the present invention, laser scanning paths may be chosen which are perpendicular to the direction of minimal principal strain. However, one skilled in the art would recognize that the application of the invention does not require a scanning path which is perpendicular to the direction of minimal principle strain.

[0043] The principle direction, θ_p, and the principal strains, $\varepsilon_{1,2}$, are readily determined by the plane-strain formulation

$$\theta_p^i = \frac{1}{2}\arctan\left(\frac{\gamma_{xy}^i}{\varepsilon_{xx}^i - \varepsilon_{yy}^i}\right) \tag{6-1}$$

$$\varepsilon_{1,2}^i = \frac{1}{2}\left(\varepsilon_{xx}^i + \varepsilon_{yy}^i \pm \sqrt{\left(\varepsilon_{xx}^i - \varepsilon_{yy}^i\right)^2 + (\gamma_{xy}^i)^2}\right) \tag{6-2}$$

where ε_{xx}, ε_{yy}, and γ_{xy} are determined from the large-deformation elastic FEM and i=0 for in-plane and 1 for bending strain, respectively.

[0044] Equation (6-1) may represent the direction of either of the two perpendicular principal strains in the plane. The direction for minimal principal stress ε_2 may be ascertained using the strains and the angle θ_p found in equation (6-1), as follows:

$$\varepsilon' = \frac{1}{2}\left(\left(\varepsilon_{xx} + \varepsilon_{yy}\right) + \left(\varepsilon_{xx} - \varepsilon_{yy}\right)\cos 2\theta_p + \gamma_{xy}\sin 2\theta_p\right). \tag{6-3}$$

[0045] If ε' is equal to ε_1, θ_p represents the direction of maximal principal strain and vise verse. Fig. 6 shows magnitude contour plots of minimal principal in-plane and bending strain for a pillow shape. As noted above, it would be apparent to one skilled in the art that application of these techniques is not limited only to pillow shapes. These techniques may be applied to innumerable different curved shapes.

[0046] Again referring to Fig. 4, the next step 44 in an exemplary embodiment of the present invention is to determine the laser scanning paths. The type of given doubly curved shapes requires both in-plane and bending strains to general and laser forming generally results both in-plane and bending strains. Furthermore, the highest compressive strains occur in a direction perpendicular to a scanning path. Therefore a scanning path may be chosen as perpendicular to the direction of the in-plane strain if its magnitude is much greater than that of the bending strain as in the case of many thin plates. As illustrated in Fig. 7, the magnitude of the in-plane strain is an order of magnitude higher than the bending strain may be determined and represented as vector plots of minimal principal in-plane strains for the desired curved shape, where the orientation of the vectors 61 represents the direction of the minimal principal in-plane strain and the length of the vectors represents the magnitude of the minimal principal in-plane strain. Scanning paths 70 may be traced perpendicular to the vectors representing the minimal principal in-plane strain 61. Fig. 7 shows an exemplary set of scanning paths, superimposed on the vector field 60 of minimal principal in-plane strain.

[0047] In determining the spacing of adjacent scanning paths, a number of factors may be considered, depending on the particular implementation of the present invention. In general, smaller spacing between adjacent scanning paths can yield more precise desired shapes and a lower required energy input for each path. However, an increased number of scanning paths can increase the time for completion of the laser forming process, and adjacent paths which are spaced too close may no longer be considered independent of each other (i.e., they may have considerable overlapping effects). To determine the properties for the heating condition, a database may be used which is constructed solely using independent scans, this ignoring any overlapping effects and degrading accuracy. Additionally, non-uniform spacing may be desirable because strains vary from one region to the other. Larger strains generally may require smaller spacing.

[0048] In an exemplary embodiment of the present invention, spacing between two adjacent paths, d_{paths}, may be equal to strain generated by laser forming, ε_{laser}, multiplied by laser beam spot size, d_{laser} (because a vast majority of the laser-generated stain is within the region covered by the laser spot), divided by the average principal minimal strain ε_2^i over the spacing, that is:

$$d_{paths} = \frac{\varepsilon_{laser} d_{laser}}{ave(\varepsilon_2^i)} \qquad (7)$$

[0049] Another practical consideration which the present invention may account for is the initialization and termination of a scanning path. In one exemplary embodiment of a method according to the present invention, a threshold may be applied such that only 90% of the total area or scanning path will be scanned. The 10% excluded area may represent the regions having smallest strains. For a pillow shape, the 10 % excluded area may be concentrated at the corners, while for the saddle shape the excluded area may be concentrated at the center.

[0050] Referring again to Fig. 4, after determination of the scanning paths, the next steps 45 and 46 in an exemplary embodiment of the present invention may be to determine a heating condition, that is, a required energy input, which is determined by laser power and laser scanning velocity (assuming that laser beam spot size and work material are given). There may be multiple solutions to this problem because many power and velocity combinations may meet the requirements of the particular application to yield the desired result. Accordingly, in an exemplary embodiment according to the present invention, a constant value for laser power may be selected for each scanning path, and the heating condition may be varied along the path by varying the scanning speed at particular points as necessary. However, one skilled in the art will realize that, within the scope of this invention, a constant scanning velocity may alternatively be selected, and the heating condition and energy input over a particular path may be modified by varying the laser power.

[0051] In one exemplary embodiment, the in-plane or bending minimal principal strains may be averaged in step 45 along a scanning path and lumped between adjacent paths for all the paths determined above. As illustrated in Fig. 8, the averaged strain may then be entered into a database which contains relationships 80 between minimal principal strains averaged within the heating zone 81 (i.e., the laser beam spot size) vs. laser power 82 and scanning velocity 83. The database may be created using numerous methods, including by employing FEM of independent scans and various modeling techniques. Given the averaged strain, a horizontal intersection of the surfaces shown in the graph of Fig. 8 can be made, which represents a set of laser power and scanning velocity combinations. The method may select a laser power level in step 46 from the intersection in the database table for the scan such that laser power levels selected for all scans are attainable with existing laser forming equipment. Additionally, other practical considerations may be employed within the scope of the present invention when selecting the values for the process variables. A single power level may be selected for each path.

[0052] In step 47, each path may be divided into segments with identical or similar values. As illustrated in Fig. 9, scanning velocity of each segment may then be determined based on the local strain and laser power chosen for the path, again using the database chart of Fig. 8 to determine a corresponding scanning speed for the particular segment 92 (shown between points 91 and 93 as a segment with constant strain values).

[0053] Thereafter, in step 48, a look-up table or database chart as shown in Fig. 8 may be used to determine a laser scanning velocity for each segment identified in step 47, based on the laser power chosen in step 46 and any practical considerations such as equipment limitations, etc. Upon completion of step 48, suitable values will have been identified for all necessary laser forming process parameters.

[0054] Referring to Fig. 10, a system according to the present invention is shown. The system may be any computer, and may preferably be a standard personal computer. As shown in Fig. 10, the computer system 100 may include computer 102 which contains at least a processor and memory, and may further preferably include a monitor 101 for visual presentation of data to a user. However, as would be known to one skilled in the art, the present invention is not limited to use in the particular system shown. In fact, any computer system which contains at least a processor and memory of sufficient processing and storage capacity to perform the computational tasks discussed herein may be used in accordance with the present invention.

[0055] The foregoing merely illustrates the principles of the invention. Various modifications and alterations to the described embodiments will be apparent to those skilled in the art in view of the teachings herein. It will thus be appreciated that those skilled in the art will be able to devise numerous systems and methods which, although not explicitly shown or described herein, embody the principles of the invention and are thus within the spirit and scope of the invention.

CLAIMS

1. A method for determining one or more parameters for controlling a laser forming process, comprising the steps of:

(a) receiving a model of a curved shape representing a three dimensional thin metal plate;

(b) determining a strain field corresponding to the model of the curved shape, the strain field comprising a plurality of points;

(c) determining minimal principle in-plane strain vectors for two or more of the plurality of points of the strain field; and

(d) determining one or more laser scanning paths, based on the determined minimal principal in-plane strain vectors, for one or more points of the strain field.

2. The method of claim 1, wherein the step of determining a strain field is performed by using large-deformation elastic finite element method.

3. The method of claim 1, further comprising the step of determining one or more average laser power values for the determined one or more laser scanning paths.

4. The method of claim 3, wherein the step of determining one or more average laser power values further comprises considering the determined minimal principle in-plane strain for points located between the determined one or more adjacent laser scanning paths.

5. The method of claim 3, further comprising the step of determining one or more laser powers based on the one or more determined average laser power values.

6. The method of claim 5, further comprising the step of segmenting the one or more determined laser scanning paths into a plurality of segments.

7. The method of claim 5, wherein the step of determining one or more laser powers further comprises obtaining one or more values for laser power from a table.

8. The method of claim 5, wherein the step of determining one or more laser powers further comprises considering practical limitations.

9. The method of claim 6, further comprising the step of determining a scanning velocity for one or more of the identified segments.

10. The method of claim 7, wherein the step of determining a scanning velocity further comprises obtaining a value for scanning velocity from a table.

11. The method of claim 9, wherein the step of determining a scanning velocity further comprises considering practical limitations.

12. A method for determining a strain field, comprising the steps of:

(a) receiving a computer model of a three-dimensional curved shape;

(b) placing the computer model of a three-dimensional curved shape between a first and a second computer model of flat plates, the first computer model of a flat plate located above the computer model of a three-dimensional curved shape, the second computer model of a flat plate located below the computer model of a three-dimensional curved shape;

(c) incrementally moving the first and second computer models of flat plates closer together, upon each movement measuring a strain at each of a plurality of points,which results from the compression of the computer model of a three-dimensional curved shape between the first and second computer models of flat plates, until the computer models of flat plates are separated by a distance equal to the thickness of a plate which composed the computer model of a three-dimensional curved shape;

(d) combining one or more values for stresses and strains, as measured at the plurality of points, to produce a strain field.

13. A system for determining one or more parameters for controlling a laser forming process, comprising:

(a) a data storage, and

(b) a processor, coupled to the data storage, operable to:

- receive a model of a curved shape representing a three dimensional thin metal plate;

- determine a strain field corresponding to the model of the curved shape, the strain field comprising a plurality of points;

- determine minimal principle in-plane strain vectors for two or more of the plurality of points of the strain field; and

- determine one or more laser scanning paths, based on the determined minimal principal in-plane strain vectors, for one or more points of the strain field.

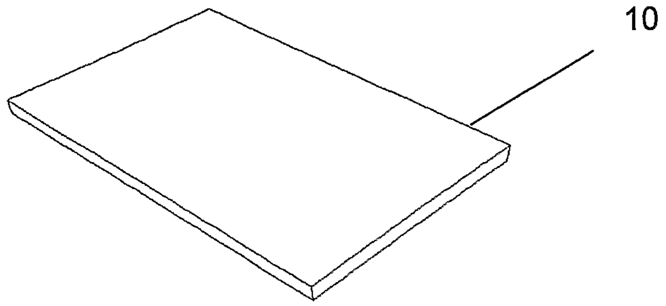

FIG. 1

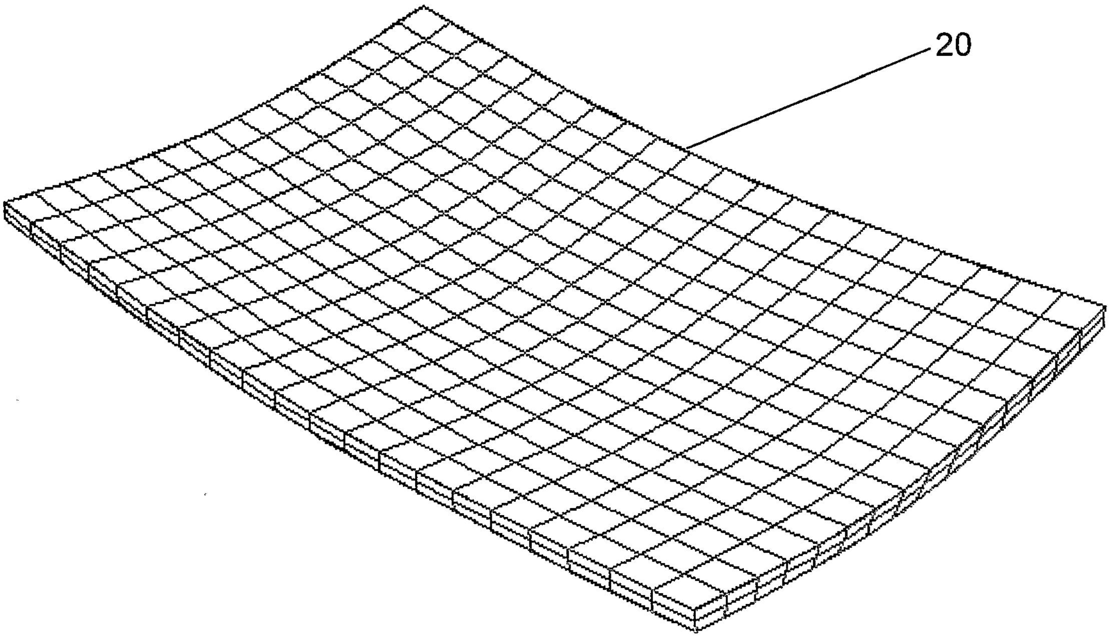

FIG. 2

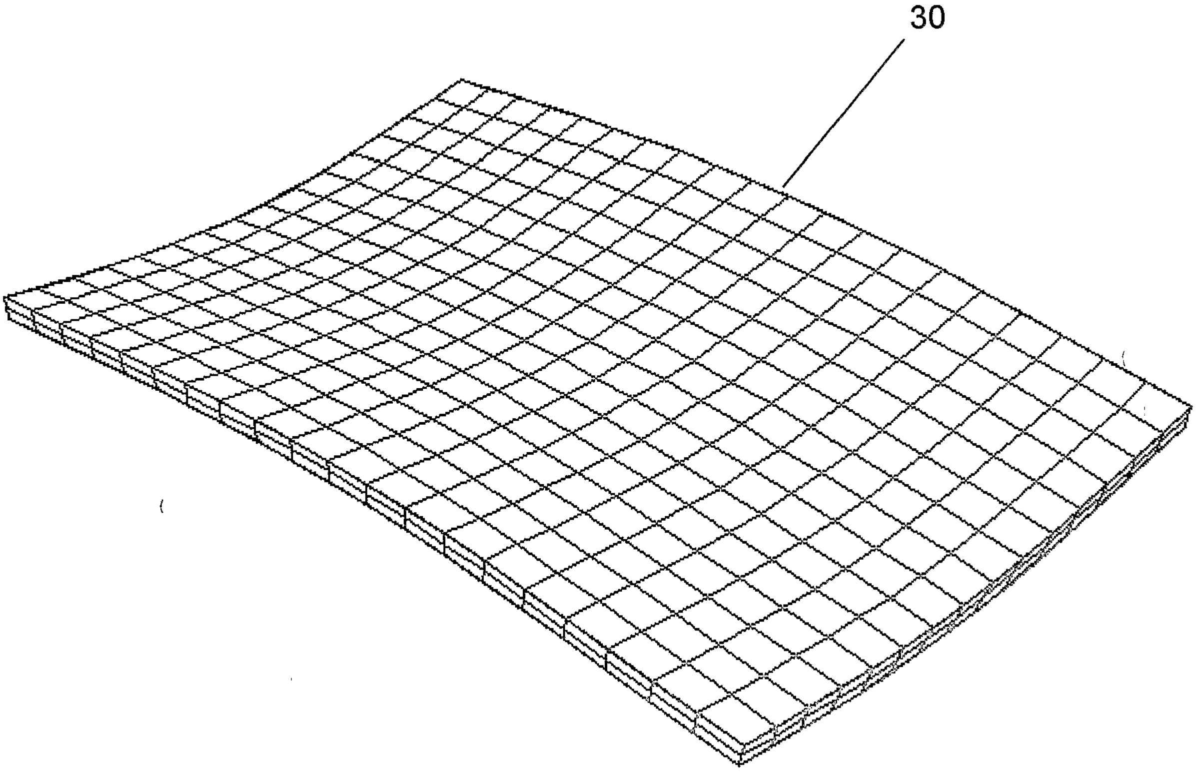

FIG. 3

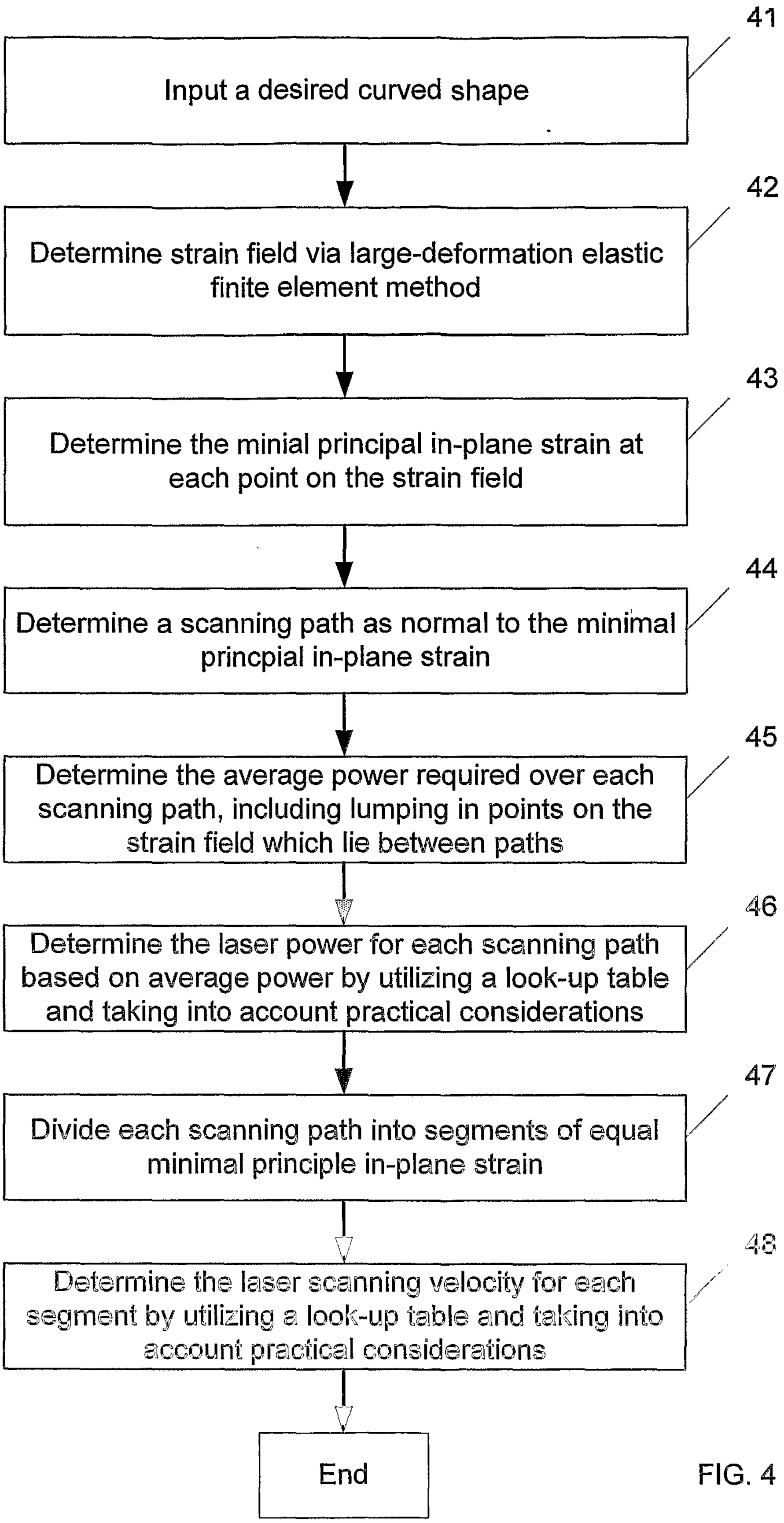
41
Input a desired curved shape
42
Determine strain field via large-deformation elastic finite element method
43
Determine the minial principal in-plane strain at each point on the strain field
44
Determine a scanning path as normal to the minimal princpial in-plane strain
45
Determine the average power required over each scanning path, including lumping in points on the strain field which lie between paths
46
Determine the laser power for each scanning path based on average power by utilizing a look-up table and taking into account practical considerations
47
Divide each scanning path into segments of equal minimal principle in-plane strain
48
Determine the laser scanning velocity for each segment by utilizing a look-up table and taking into account practical considerations
End

FIG. 4

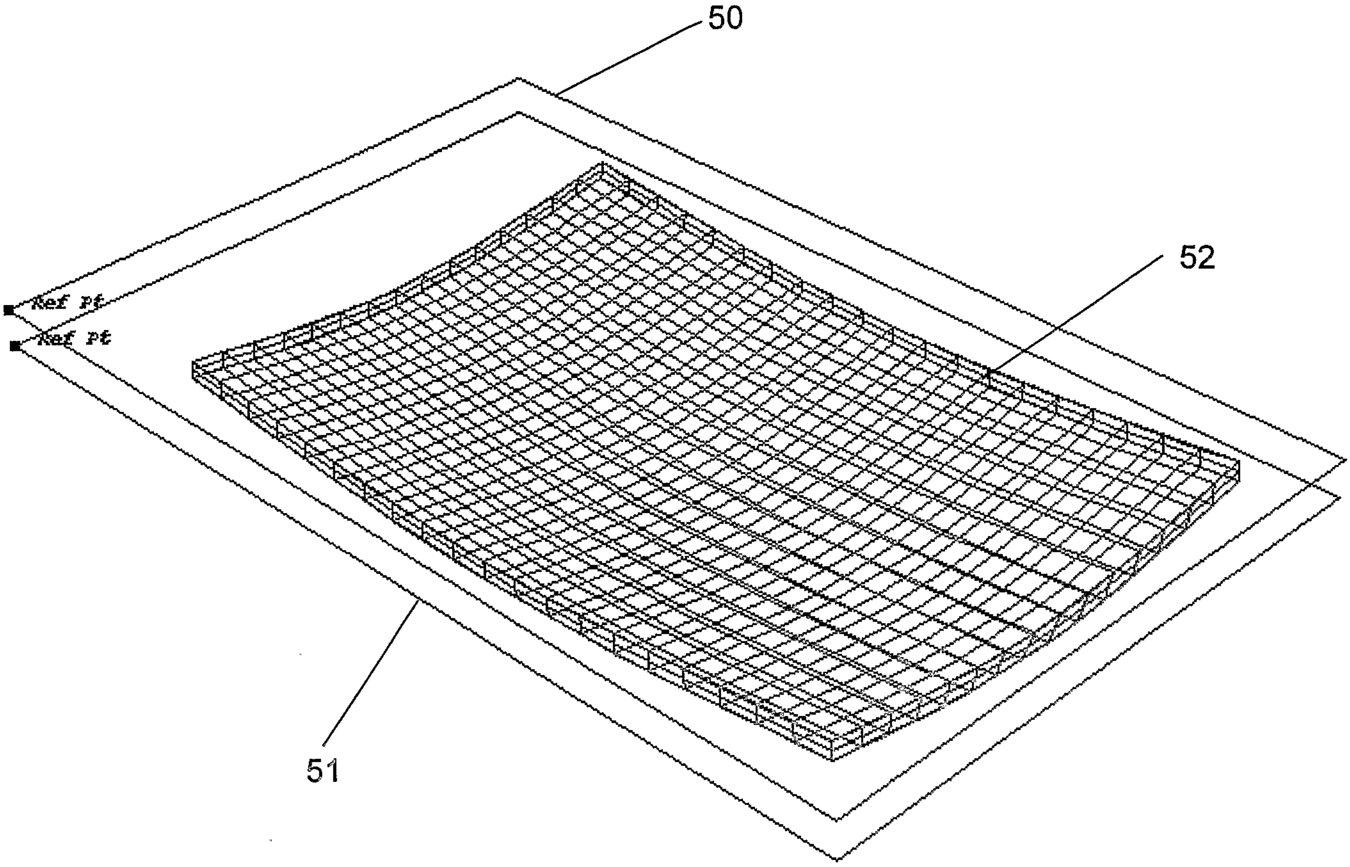

FIG. 5

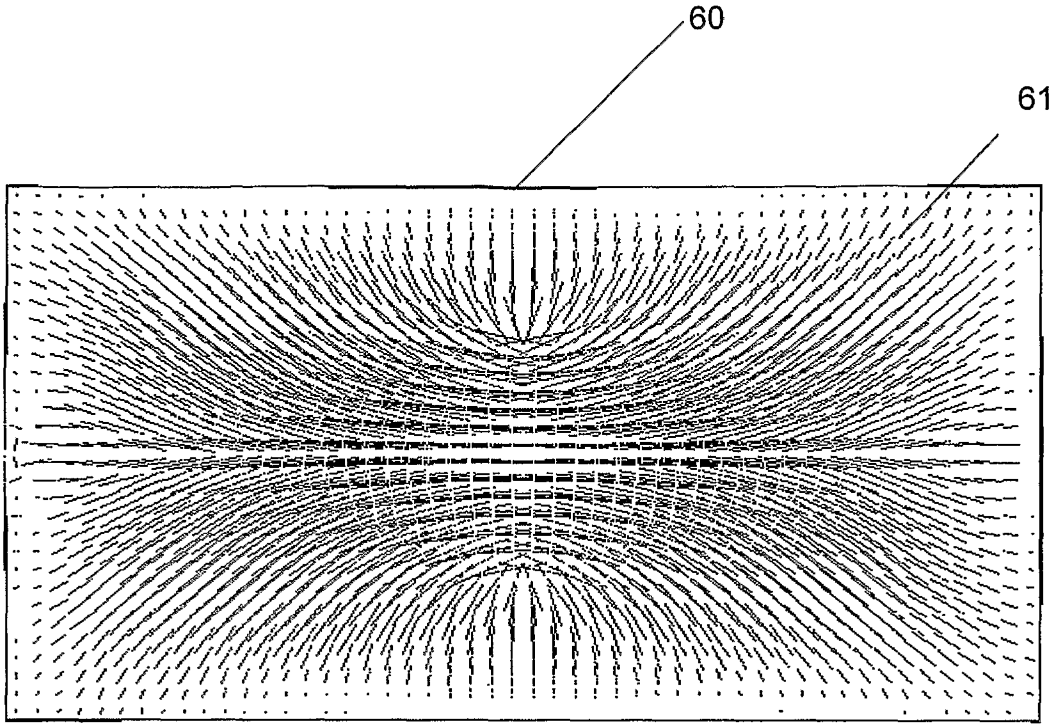

FIG. 6

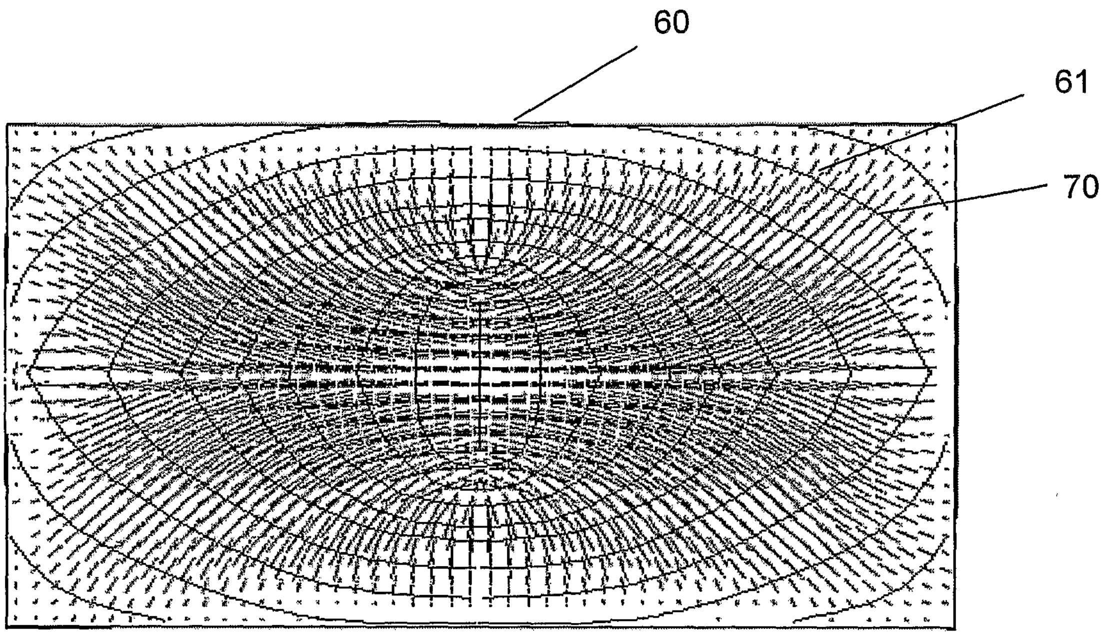

FIG. 7

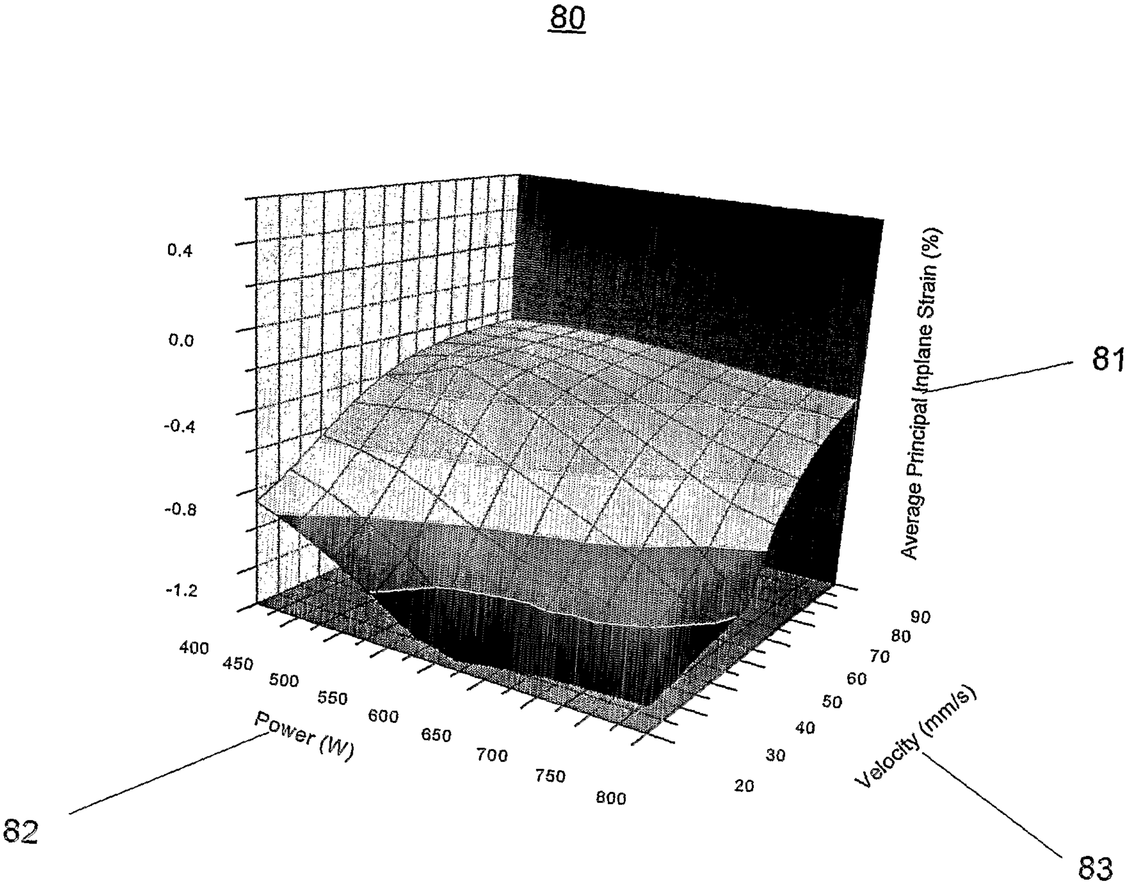
80
0.4
0.0
-0.4
-0.8
-1.2
Average Principal Inplane Strain (%)
81
400
450
500
550
600
650
700
750
800
Power (W)
82
90
80
70
60
50
40
30
20
Velocity (mm/s)
83

FIG. 8

90

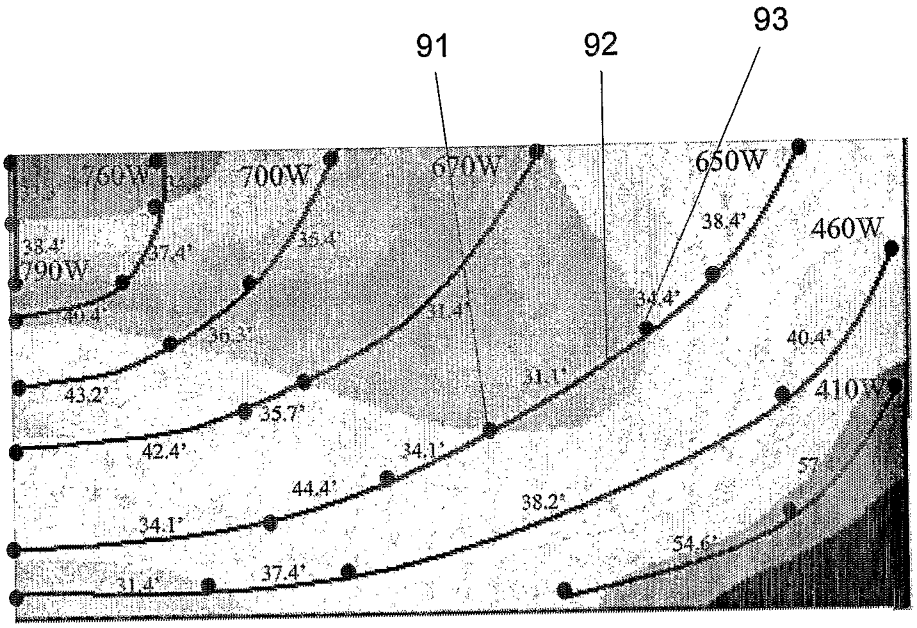
93
91
92
760W
700W
670W
650W
38.4’
460W
38.4’
37.4’
35.4’
790W
34.4’
40.4’
31.4’
36.3’
40.4’
31.1’
43.2’
35.7’
410W
42.4’
34.1’
44.4’
57
34.1’
38.2°
54.6’
37.4’
31.4’

FIG. 9

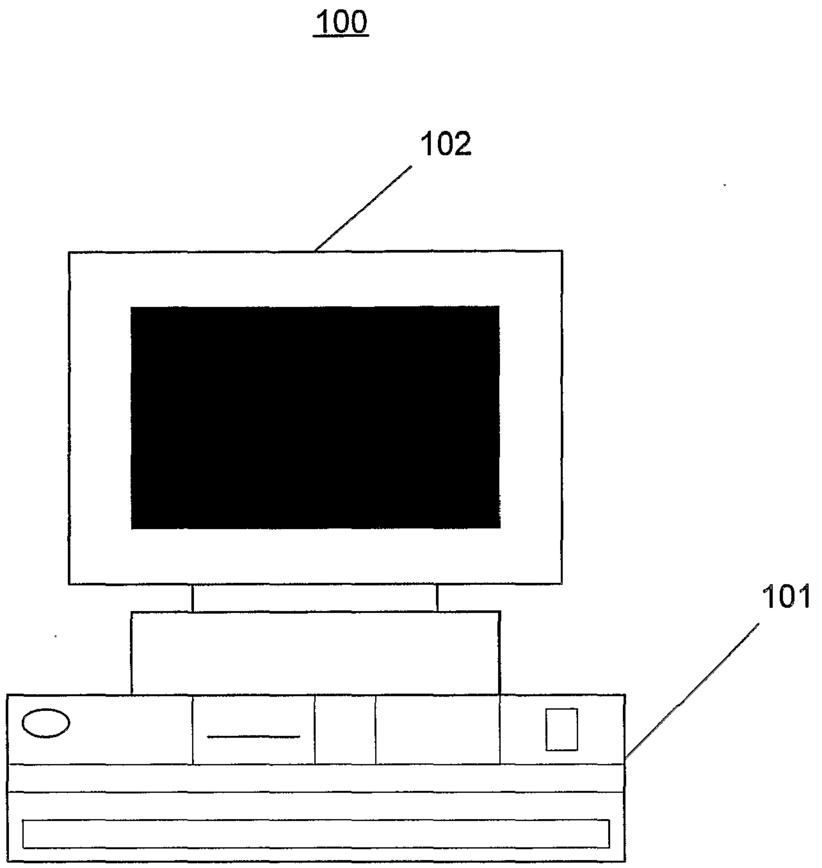

FIG. 10