



(51) International Patent Classification:
D04B 21/18 (2006.01)

(21) International Application Number:
PCT/GB2010/050719

(22) International Filing Date:
30 April 2010 (30.04.2010)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
0907544.1 1 May 2009 (01.05.2009) GB
0907558.1 1 May 2009 (01.05.2009) GB
0917538.1 7 October 2009 (07.10.2009) GB

(71) Applicants (for all designated States except US): **GLOB-AL COMPOSITES GROUP** [GB/GB]; The Old Barrel Store, Drayman's Lane, Marlow, Buckinghamshire SL7 2FF (GB). **AUXETIC TECHNOLOGIES LTD** [GB/GB]; The Old Barrel Store, Drayman's Lane, Marlow, Buckinghamshire SL7 2FF (GB).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **ANAND, Subhash** [GB/GB]; The University Of Bolton, Deane Road, Bolton, Lancashire BL3 5AB (GB). **SKERTCHLY, David** [GB/GB]; 7 Sandringham Court, Winn Road, Southampton, Hampshire SO17 1EN (GB).

(74) Agent: **OLSWANG**; 90 High Holborn, London, Greater London WC1V 6XX (GB).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

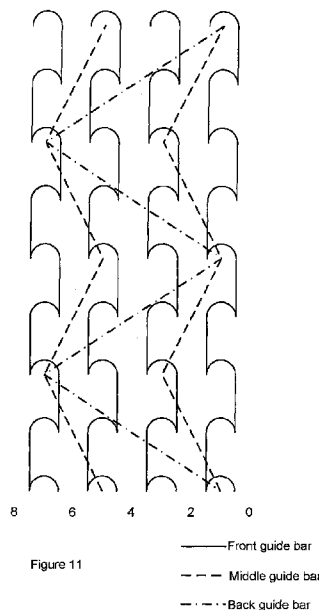
(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

[Continued on next page]

(54) Title: AUXETIC KNITTED FABRIC



(57) Abstract: An auxetic knitted fabric, comprising an auxetic component knitted from at least a first type of fibre, and a stabilising component knitted from at least a second type of fibre, wherein the first and second fibre types have different mechanical properties.



— *before the expiration of the time limit for amending the
claims and to be republished in the event of receipt of*

amendments (Rule 48.2(h))

AUXETIC KNITTED FABRIC

Background

The current invention relates to the manufacture of knitted auxetic fabrics.

The Poisson's ratio of a material is a measure of its expansion or contraction in a direction perpendicular to an applied strain. Materials with a positive Poisson's ratio contract in a direction perpendicular to an applied tensile strain whereas materials having a negative Poisson's ratio expand in a direction perpendicular to an applied tensile strain. Materials having a negative Poisson's ratio are known as auxetic materials.

A variety of materials have been manufactured with auxetic properties, for example foams (US 4,668,557), fibres (WO00/53830) and honeycombs.

Conventional, positive Poisson's ratio materials do not naturally form synclastic curves. However, many aspects of the human body are in the form of synclastic curves and therefore it is difficult to provide a garment which naturally forms a close fit to those aspects of the body using a single sheet of fabric without wrinkling of the fabric. In contrast, auxetic materials often naturally form synclastic curves and may therefore provide an improved fabric for clothing manufacture. Auxetic fabrics may also find many other applications in which a thin material having auxetic properties is desirable.

WO2009/002479 describes a variety of net fabrics, some having negative Poisson's ratios. Net fabrics are only suitable for use in particular applications, and are not useful as general-purpose fabrics due to the large open spaces, as seen in Figures 3 and 4, that characterise net fabrics. Furthermore, many of the fabrics disclosed in that document do not have any elastic component, and therefore would not return to their original shape after deformation, making them impractical for most uses.

Summary

The following presents a simplified summary of the disclosure in order to provide a basic understanding to the reader. This summary is not an extensive overview of the disclosure and it does not identify key/critical elements of the invention or delineate the scope of the invention. Its sole purpose is to present some concepts disclosed herein in a simplified form as a prelude to the more detailed description that is presented later.

There is provided an auxetic solid knitted fabric, comprising an auxetic component knitted from at least a first type of fibre, and a stabilising component knitted from at least a second type of fibre, wherein the first and second fibre types have different mechanical properties.

Optional features of the invention are set out in the claims.

Description of the drawings

Embodiments of the present invention will now be further described, by way of example, with reference to the drawings, wherein:-

Figure 1 shows schematic diagrams of structures that have been shown to be auxetic;

Figure 2 shows a schematic diagram of an auxetic fabric;

Figure 3 shows a schematic diagram of the fabric shown in Figure 3 after deformation;

Figure 4 shows a schematic diagram of the fabric shown in Figure 3 after non-auxetic deformation by stretching of the ribs in the x-direction;

Figure 5 shows a schematic diagram of a further fabric displaying auxetic properties;

Figure 6 shows a schematic diagram of an auxetic shape including indications of dimensions used in the equations;

Figure 7 shows a graph of calculated values for the Poisson's ratio as a function of the angle β ;

Figure 8 shows a schematic diagram of an auxetic shape including indications of dimensions used in the equations;

Figure 9 shows a graph of Poisson's ratio as β and l vary, with α and m remaining constant;

Figure 10 shows a graph of Poisson's ratio against a ratio of l/m calculated using equation (2);

Figure 11 shows a first stitch pattern;

Figure 12 shows a photograph of a fabric knitted using the first stitch pattern;

Figure 13 shows a schematic diagram of a testing system;

Figure 14 shows a series of photographs of the fabric shown in Figure 12 undeformed and under 10% strain;

Figure 15a shows plots of width and length for the fabric of Figure 13 subject to tensile load application along the x direction;

Figure 15b shows a plot of the transverse strains of the middle 4 width sections of Figure 15a as a function of axial strain;

Figures 16a to d show plots of length and width against time for the fabric shown in Figure 13;

Figures 17a to d show plots of widthwise strain against lengthwise strain for the fabric shown in Figure 13;

Figure 18 shows a second stitch pattern;

Figure 19 shows a photograph of a fabric knitted using the second stitch pattern;

Figure 20 shows a series of photographs of the fabric shown in Figure 18 undeformed and under 10% strain;

Figures 21 show plots of length and width against time for the fabric shown in Figure 18;

Figures 22a to d show plots of widthwise strain against lengthwise strain for the fabric shown in Figure 18;

Figure 23 shows a third stitch pattern;

Figure 24 shows a photograph of a fabric knitted using the third stitch pattern;

Figure 25 shows a series of photographs of the fabric shown in Figure 24 undeformed and under 10% strain;

Figures 26a to d show plots of length and width against time for the fabric shown in Figure 24;

Figures 27a to d show plots of widthwise strain against lengthwise strain for the fabric shown in Figure 24;

Figure 28 shows a fourth stitch pattern;

Figure 28a shows a loop diagram from the stitch pattern of Figure 28;

Figure 29 shows a photograph of a fabric knitted using the fourth stitch pattern;

Figure 30 shows a series of photographs of the fabric shown in Figure 28 undeformed and under 10% strain;

Figures 31a to d show plots of length and width against time for the fabric shown in Figure 28;

Figures 32a to d show plots of widthwise strain against lengthwise strain for the fabric shown in Figure 28; and

Figure 33 shows photographs of a 12 gauge fabric made using the stitch pattern of Figure 28.

Detailed description

The detailed description provided below in connection with the appended drawings is intended as a description of the present examples and is not intended to represent the only forms in which the present example may be constructed or utilized. The description sets forth the functions of the example and the sequence of steps for constructing and operating the example. However, the same or equivalent functions and sequences may be accomplished by different examples.

The description below is given with regard to a warp knitted fabric, but as will be appreciated other knitting systems may be utilised to apply the principles described herein.

Materials have been demonstrated to possess auxetic properties by virtue of both microscopic (e.g. particular particle configuration in polymers), and macroscopic features (e.g. honeycomb materials having particular geometric structures). Figure 1 shows schematically two geometric patterns that have been shown to be auxetic.

The auxetic effect may be achieved at a macroscopic level by a number of mechanisms including rib or shape rotation or flexure. For example, the cellular frameworks of re-entrant struts (ribs) of Figure 1 deform by rib flexing or rotation to expand their re-entrant side(s).

Modern knitting machine technology allows the formation of complex, and relatively arbitrary, shapes formed by the fibre paths within a knitted fabric. The current invention provides fabrics, and methods of manufacture of fabrics, that display auxetic behaviour by reproducing the geometry of auxetic structures in the knit fabric structures.

Figure 2 shows a schematic diagram of a knitted fabric having auxetic properties in the y direction – that is, a tensile load applied in the y direction causes an increase in width in the x direction. The fabric is also auxetic in the x direction. The fabric is formed of two components – an auxetic component 30 and a stabilising component 31. In the figures of this application, dashed lines are utilised to differentiate types of fibres, or fibres forming different components of the fabric. The non-continuous nature of those lines does not indicate that the fibres are not continuous, but are simply used to differentiate between fibres for clarity in the absence of the ability to use colour.

The fabric shown schematically in Figure 2 is knitted from fibres to form the fabric from selected fibres. As will be appreciated, many techniques may be utilised to knit a fabric having the design shown in Figure 2 and examples of possible patterns and systems are provided below.

The auxetic component is formed using relatively high modulus fibres and the stabilising component is formed using relatively low modulus, elastic, fibres. During the knitting process the fibres of the two components may be knitted together, one component may

be laid into the other one, or a combination of knitting and laying in may be utilised between the two components.

Under load the auxetic component deforms such that the Poisson's ratio of the fabric is negative. Once the load has been removed, the stabilising component acts to return the fabric to its relaxed, unloaded state.

As a load is applied in the x-direction the higher modulus ribs of the auxetic component retain their length and deform by rotation around the vertices of the shapes. The effect of this is to deform the shapes towards regular, rather than re-entrant, triangles as shown in Figure 3. As the re-entrant base of each shape moves to a straight base (i.e. from Figure 2 to Figure 3), the central vertex, to which the adjacent shape is linked, pushes that adjacent shape horizontally, thereby causing the fabric to expand in the y direction. The dotted outline 40 in Figure 3 shows the relative size of the fabric in its unstretched form, clearly showing expansion in both axes in response to a stretching force being applied in one direction, thereby exhibiting a negative Poisson's ratio.

The fibres of the stabilising component are stretched by the application of the load in the x-direction, thereby allowing movement of the vertices of the auxetic component to provide the deformation described above. The stabilising fibres also move in the y direction as the vertices at which they are attached are moved by the auxetic component.

When a load which has stretched the fabric towards that shown in Figure 3 is released, the fibres of the stabilising component (which, as noted previously, are elastic) act to pull the auxetic component back to the rest state shown in Figure 2. The fabric therefore returns to its original structure and can provide repeated performance.

Once the auxetic component has reached the configuration shown in Figure 3, no further expansion is possible in the x direction without stretching of the fibres forming the auxetic component. It is expected that if a load is applied in the x-direction at a high enough level, further stretching of the fabric will occur by stretching of the fibres forming the bases of the triangles, and rotation and/or stretching of the other fibres in the auxetic fabric. Figure 4 shows a schematic diagram of the expected structure during this further expansion. The dashed square 50 shows the relative size of the fabric when the auxetic component is fully deformed but without any stretching of the fibres forming the auxetic component. As can be seen the width of the fabric has decreased and therefore a

positive Poisson's ratio is demonstrated. Deformation during this second phase is predominantly by stretching of those fibres of the auxetic component aligned along the loading (x) direction and rotation of those fibres of the auxetic component oriented at an angle to the loading (x) direction. As explained previously the modulus of those fibres is larger than the fibres of the stabilising component and therefore the modulus of the material in this second phase is larger than in the first, negative Poisson's ratio, phase. For this same reason deformation in this second phase is dominated by the fibres of the auxetic component and therefore the stabilising component has little, or no, effect on this second phase behaviour.

For tensile loading along the y direction, the base of each re-entrant triangle first moves to a straight line configuration and then adopts a convex rather than the original concave (re-entrant) shape upon further loading. Rotation of the fibres in a convex (as opposed to re-entrant) triangular network formed by the auxetic component leads to extension along the length in the y direction being accompanied by a reduction in width along the x direction. Deformation during the second phase for loading along y is then predominantly by rotation of the fibres of the auxetic component.

In summary, the knitted fabric shown schematically in Figure 2 has a negative Poisson's ratio, that is it is auxetic, in a first phase of stretching of the fabric. During this phase stretching of the fabric is by stretching of the fibres of the stabilising component and by rotation of the fibres of the auxetic component about their vertices. This rotation causes the re-entrant triangles of the auxetic component to deform towards regular triangles, and thus the fabric to have a negative Poisson's ratio. The modulus of the material during the first phase is defined by the modulus of the fibres of the stabilising component, and the resistance of the fibres of the auxetic component to the rotation movement. This latter resistance is dependent on the knit pattern, the type of fibres utilised for the auxetic component and the relative properties of the fibres of the auxetic and stabilising components. The actual overall modulus, is therefore a function of the properties of the fibres of both components, their relative values and also the knit pattern used. Furthermore, the Poisson's ratio of the fabric is also dependent on all of these parameters since the Poisson's ratio is defined by the manner in which the fabric deforms as it stretches.

The behaviour of the fabric will depend on the relative behaviours of the fibres and components they form. For example, the fibre of the auxetic component must have a sufficiently high modulus compared to the resistance to rotation of that fibre about its

vertices, such that the shapes of the auxetic component deform in preference to the fibres of the auxetic component stretching.

The elasticity of the fibres of the stabilising component must be sufficiently high compared to the resistance of the fibres of the auxetic component to rotation that the stabilising component can return the auxetic component to its original configuration after release of the stretching force. It is therefore likely that the modulus of the fabric will be dominated by the modulus of the stabilising component. Similarly the modulus of the fibres of the auxetic component should be sufficiently high compared to the resistance to rotation such that the auxetic component deforms by rotation rather than buckling of the fibres forming the component.

Figure 5 shows a schematic of a further fabric expected to demonstrate auxetic properties. The fabric of Figure 5 is similar to the fabric of Figures 3 to 5 in that it is formed of an auxetic component and a stabilising component. The layout is related to that of Figures 3 to 5 in that it is obtained by the removal of one of the sides from each of the re-entrant triangles to combine two adjacent triangles into a single shape. The resulting shapes are similar to the bow-tie shapes utilised in auxetic honeycomb structures.

In an idealised model of the knit structures, deformation of the fabric can be assumed to be solely due to rotation of the fibres of the auxetic component about its vertices. That is, solely due to a transformation from Figure 2 to Figure 3, with no stretching of the fibres of the auxetic component and no resistance to rotation at the vertices such that no bending of the fibres of the auxetic component occur.

On the basis of these assumptions about the mechanisms of deformation, the Poisson's ratio can be calculated from geometry using equation (1). The symbols of equation (1) are shown in Figure 6.

$$\nu_{xy} = \nu_{yx}^{-1} = -\frac{dY}{Y} \frac{X}{dx} = -\tan \alpha \tan \beta \quad (1)$$

Figure 7 shows a graph of calculated values for the Poisson's ratio as a function of the angle β . As would be expected from a simply geometrical consideration of the shapes seen in the structure, the model predicts negative Poisson's ratios for $\beta < 90^\circ$.

Equation (1) suggests that in order for the structure to be auxetic β must be $< 90^\circ$. However, if other deformation mechanisms are considered negative Poisson's ratios may also be obtained for $\beta > 90^\circ$. Figure 8 shows the symbols used in the following discussion. A possible deformation mechanism, in structures having $\beta > 90^\circ$, is for ribs AB and BC to stretch as angle β decreases (α and m remain constant), thereby compensating for an increase in AC due to the decrease in β . For this mode of deformation the Poisson's ratio can be shown to be calculated by equation (2).

$$\nu_{xy} = \nu_{yx}^{-1} = \frac{(1 + \tan \alpha \tan \beta)}{\left(\frac{m \cos \beta}{l \cos \alpha} - 1 \right)} \quad (2)$$

Figure 9 shows a graph of Poisson's ratio as β and l vary, with α and m remaining constant.

Figure 10 shows a graph of Poisson's ratio against a ratio of l/m calculated using equation (2). As seen in that figure negative Poisson's ratios may be obtained for certain values of l/m .

Equation (2) and Figures 9 and 10 demonstrate that negative Poisson's ratios may be obtainable for values of $\beta > 90^\circ$ for certain deformation mechanisms. As has been discussed previously, the deformation mechanism is defined by the relative properties of the fibres and knit structure.

A number of stitch patterns were designed for implementation on a knitting machine to knit structures corresponding to the structure illustrated schematically in Figure 2 and to explore various parameters which may affect the Poisson's ratio of the resulting fabric.

Figure 11 shows a first stitch pattern designed to manufacture a fabric functionally equivalent to that shown schematically in Figure 2. The pattern utilises three types of fibres, two to form the auxetic component and one to form the stabilising component. In this pattern the auxetic component is laid into the stabilising component which is knitted using open loop stitches.

The stitch pattern can be implemented using three guide bars set as shown in Table 1. The nomenclature 0-2 refers to a jump of one needle.

Bar	Setting
Front	0-2/2-0 (Full set)
Middle	0-0/2-2/4-4/2-2 (1 in – 1 miss)
Rear	0-0/4-4/8-8/4-4 (1 in – 1 miss)

Table 1

A fabric was knitted using the stitch pattern shown in Figure 11. An 18 gauge machine was utilised with the fibres shown in Table 2.

Bar	Setting
Front	Double covered lycra
Middle	Mono-filament PES 0.15mm
Rear	Mono-filament PES 0.25mm

Table 2

Other settings of the machine were configured to the values expected to produce a fabric having the desired structure.

Figure 12 shows a photograph of the knitted fabric produced using the stitch pattern of Figure 11 and the settings of Tables 1 and 2. As can be seen the auxetic component of the fabric does not have the re-entrant triangle configuration of Figure 2 as intended, but instead the base of the triangle is actually directed out of the shape.

The fabric was heat set prior to mechanical testing. Test samples (15cm long by 5 cm wide) were cut along and perpendicular to the warp (X) direction, and also at $\pm 45^\circ$ to the warp direction. Fiducial markers were placed on the samples using marker pen to enable accurate measurement of strains by optical means during mechanical testing. Testing of the fabric was performed using the system shown in Figure 13. The fabric concerned was loaded into the jaws of the universal testing machine for measurement of its stress/strain characteristics, and a camera system enabled the measurement of dimensional changes from the fiducial markers on the sample during the application of a load to the fabric. The fabric was measured for uniaxial loads applied in the X and Y

directions, and also at -45° to the X direction (direction 1) and $+45^\circ$ to the X direction (direction 2).

Figure 15 shows a series of photographs taken during testing of the fabric. The photos in the left hand column show fabric unloaded, while the photos in the right hand column show the fabric with a 10% length-wise strain. Each of the rows relates to one of the testing directions, as noted in the row heading.

Videoextensometry data provided measurements of the length and width of the fabric while a longitudinal strain is applied. By way of demonstration of the method of measuring Poisson's ratios for the fabrics, Figure 15a shows the width and length videoextensometry data for the fabric of Figure 13 subject to tensile load application along the x direction (along the warp direction). There are 1 length curve (thick line) and 10 width curves, corresponding to 10 individual transverse sections along the length of the fabric. Length extension is accompanied by width contraction, characteristic of a material possessing positive Poisson's ratio behaviour.

Data from the middle 4 of the 10 width sections were used in the subsequent data analysis to minimise possible artefacts due to edge effects associated with the width sections nearest the grips of the testing machine.

The width and length data were converted to transverse and axial strains, respectively, using the definition of true strain given by equation (3):

$$\varepsilon_l = \ln\left(\frac{l}{l_0}\right) \quad (3)$$

where l and l_0 are the length and original length in the direction of interest.

Figure 15b shows the transverse strains of the middle 4 width sections as a function of axial strain.

The Poisson's ratio ν_{ij} (change in width along transverse direction j to a stretch along direction i) is then given by equation (4):

$$\nu = -\left(\frac{\text{strain}_j}{\text{strain}_i}\right) = -\frac{\varepsilon_j}{\varepsilon_i} \quad (4)$$

The Poisson's ratio is thus given by the negative of the gradient of the curves shown in Figure 15b.

Best fit straight lines were fitted to the data for each width section in Figure 15b and the equations for the lines are also shown. From the equations, the Poisson's ratios of the 4 width sections for the Fabric of Figure 13 are $\nu_{xy} = +0.62, +0.45, +0.18$ and $+0.08$, yielding an average value from one test of $+0.3 \pm 0.2$ where the quoted experimental uncertainty is given by the standard deviation of the individual width sections.

Figures 16a to d show graphs, for the four orientations (x, y, -45° , $+45^\circ$ respectively), of length and average width against time as the fabric samples were stretched in the apparatus shown in Figure 13. The middle 4 of 10 width measurements were averaged to give the average width the data shown in Figure 16.

Figures 17a to d show graphs, for the four orientations (x, y, -45° , $+45^\circ$ respectively), of average widthwise strain against lengthwise strain derived from the data of Figure 16.

The measurements of the fabric were repeated a number of times and the results averaged to provide the Poisson's ratio values given in Table 3 below.

ν_{xy}	ν_{yx}	ν_{12}	ν_{21}
0.3 ± 0.3	0.04 ± 0.07	-0.02 ± 0.03	0.1 ± 0.1

Table 3

Very low (near zero) Poisson's ratios are produced in two of the orientations of the fabric.

Figure 18 shows a second stitch pattern designed to manufacture a fabric equivalent functionally to that shown schematically in Figure 2. In addition to the fibres of the stitch pattern shown in Figure 11 an additional fibre is utilised in the stabilising component of the fabric. A second elastomeric fibre is knitted to join the bases of the triangle shapes in each column. In contrast to the first fibre of the stabilising component, this fibre is knitted using closed loop stitches which was intended to provide a fabric which is more stable in both length and width directions.

The stitch pattern can be implemented using four guide bars set as shown in Table 4.

Bar	Setting
Front	2-0/2-4 (1 in – 1 miss)
2	0-2/2-0 (Full set)
3	0-0/4-4/8-8/4-4 (1 in – 1 miss)
Rear	0-0/2-2/4-4/2-2 (1 in – 1 miss)

Table 4

A fabric was knitted using the stitch pattern shown in Figure 18. An 18 gauge machine was utilised with the fibres shown in Table 5.

Bar	Setting
Front	480 dtex Dorlastan V500
2	480 dtex Dorlastan V500
3	Mono-filament PES 0.25mm
Rear	Mono-filament PES 0.15mm

Table 5

Other settings of the machine were configured to the values expected to produce a fabric having the desired structure.

Figure 19 shows a photograph of the knitted fabric produced using the stitch pattern of Figure 18 and the settings of Table 4 and Table 5. As can be seen the auxetic component of the fabric does not have the re-entrant triangle configuration of Figure 2 as intended, but the base of the triangles is significantly flatter than was achieved with the previous stitch pattern.

Testing was performed as described above.

Figure 20 shows a series of photographs taken during testing of the fabric. The photos in the left hand column show fabric unloaded, while the photos in the right hand column show the fabric with a 10% length-wise strain. Each of the rows relates to one of the testing directions, as noted in the row heading.

Figures 21a to d show graphs, for the four orientations (x, y, -45° , $+45^\circ$ respectively), of length and average width against time as the fabric samples were stretched in the apparatus shown in Figure 13. The four central widths were averaged to produce the averaged width data shown in Figure 16 to minimise possible artefacts due to edge effects associated with the width sections nearest the grips of the testing machine.

Figures 22a to d show graphs, for the four orientations (x, y, -45° , $+45^\circ$ respectively), of average widthwise strain against lengthwise strain calculated as described previously from the data of Figure 21.

The measurements of the fabric were repeated a number of times and the results averaged to provide the Poisson's ratio values given in Table 6 below.

v_{xy}	v_{yx}	v_{12}	v_{21}
0.26 ± 0.06	0.08 ± 0.04	0.04 ± 0.04	0.18 ± 0.03

Table 6

Figure 23 shows a third stitch pattern designed to manufacture a fabric equivalent functionally to that shown schematically in Figure 2. This stitch pattern is a variation of that shown in Figure 18 in that the fibres forming the bases of the triangles are knitted into the fabric using closed loop stitches in contrast to being laid-in in the previous pattern. These changes were intended to achieve more stability at the cross-over points and more stably anchor the hinges.

The stitch pattern can be implemented using four guide bars set as shown in Table 7.

Bar	Setting
Front	2-0/2-4 (1 in – 1 miss)
2	0-2/2-0 (Full set)
3	0-0/4-4/8-8/4-4 (1 in – 1 miss)
Rear	2-0/2-2/2-4/2-2 (1 in – 1 miss)

Table 7

A fabric was knitted using the stitch pattern shown in Figure 23. An 18 gauge machine was utilised with the fibres shown in Table 8.

Bar	Setting
Front	480 dtex Dorlastan V500
2	480 dtex Dorlastan V500
3	Mono-filament PES 0.25mm
Rear	Mono-filament PES 0.15mm

Table 8

Other settings of the machine were configured to the values expected to produce a fabric having the desired structure.

Figure 24 shows a photograph of the knitted fabric produced using the stitch pattern of Figure 23 and the settings of Table 7 and Table 8. This fabric is denser and tighter than the previous samples.

Testing was performed as described previously.

Figure 25 shows a series of photographs taken during testing of the fabric. The photos in the left hand column show fabric unloaded, while the photos in the right hand column show the fabric with a 10% length-wise strain. Each of the rows relates to one of the testing directions, as noted in the row heading.

Figures 26a to d show graphs, for the four orientations (x, y, -45°, +45° respectively), of length and average width against time as the fabric samples were stretched in the apparatus shown in Figure 13. The four central widths were averaged to produce the averaged width data shown in Figure 26 to minimise possible artefacts due to edge effects associated with the width sections nearest the grips of the testing machine.

Figures 27a to d show graphs, for the four orientations (x, y, -45°, +45° respectively), of average widthwise strain against lengthwise strain calculated as described previously from the data of Figure 26.

The measurements of the fabric were repeated a number of times and the results averaged to provide the Poisson's ratio values given in Table 9 below.

ν_{xy}	ν_{yx}	ν_{12}	ν_{21}
0.11 ± 0.03	0.33 ± 0.04	-0.02 ± 0.02	-0.13 ± 0.04

Table 9

This fabric sample therefore demonstrates auxetic behaviour in at least one direction, and a zero or negative Poisson's ratio in a second direction. The auxetic properties measured in the ν_{12} and ν_{21} directions is consistent with auxetic behaviour arising from the structure shown schematically in Figure 5. One of the long struts is aligned close to the loading direction, while the other long strut is redundant in terms of Poisson's ratio, but may contribute to the stiffness of the material.

Figure 28 shows a fourth stitch pattern designed to manufacture a fabric equivalent functionally to that shown schematically in Figure 2. This stitch pattern is a variation of that shown in Figure 23 in that the first fibres of the stabilising component are now knitted in a Tricot stitch with both closed and open stitches, in contrast to the pillar stitch used in the previous patterns. This modification was intended to produce a more isotropic fabric. Figure 28a shows a loop diagram expected from the stitch pattern shown in Figure 28.

The stitch pattern can be implemented using four guide bars set as shown in Table 10.

Bar	Setting
Front	2-0/2-4 (1 in – 1 out)
2	2-4/0-2 (1 in – 1 out)
3	0-0/4-4/8-8/4-4
4	2-0/2-2/2-4/2-2 (1 in – 1 out)

Table 10

A fabric was knitted using the stitch pattern shown in Figure 28. An 18 gauge machine was utilised with the fibres shown in Table 11.

Bar	Setting
Front	480 dtex Dorlastan V500
2	480 dtex Dorlastan V500
3	Mono-filament PES 0.25mm
Rear	Mono-filament PES 0.15mm

Table 11

Other settings of the machine were configured to the values expected to produce a fabric having the desired structure.

Figure 29 shows a photograph of the knitted fabric produced using the stitch pattern of Figure 28 and the settings of Table 10 and Table 11.

Testing was performed as described previously.

Figure 30 shows a series of photographs taken during testing of the fabric. The photos in the left hand column show fabric unloaded, while the photos in the right hand column show the fabric with a 10% length-wise strain. Each of the rows relates to one of the testing directions, as noted in the row heading.

Figures 31a to d show graphs, for the four orientations (x, y, -45°, +45° respectively), of length and average width against time as the fabric samples were stretched in the apparatus shown in Figure 13. The images of the fabric provided width data at ten points along the length of the sample. The four central widths were averaged to produce the averaged width data shown in Figure 31 to minimise possible artefacts due to edge effects associated with the width sections nearest the grips of the testing machine.

Figures 32a to d show graphs, for the four orientations (x, y, -45°, +45° respectively), of average widthwise strain against lengthwise strain calculated as described previously from the data of Figure 31.

The measurements of the fabric were repeated a number of times and the results averaged to provide the Poisson's ratio values given in Table 12 below.

v_{xy}	v_{yx}	v_{12}	v_{21}
0.1 ± 0.06	0.23 ± 0.05	-0.22 ± 0.03	-0.13 ± 0.02

Table 12

This fabric sample therefore demonstrates auxetic behaviour in two directions. One of the long struts is aligned close to the loading directions which demonstrated auxetic properties, while the other long strut is redundant in terms of Poisson's ratio, but may contribute to the stiffness of the material.

A further fabric was knitted using the stitch pattern of Figure 28 at 12 gauge and using the settings shown in Table 13.

Bar	Setting
Front	2-0/2-4 (1 in – 1 out), Run in 3218mm per rack
2	2-4/0-2 (1 in – 1 out), Run in 3218mm per rack
3	0-0/4-4/8-8/4-4 (1 out – 1 in), Run in 1623mm per rack
4	2-0/2-2/2-4/2-2 (1 in – 1 out), Run in 607mm per rack

Table 13

The fibres shown in Table 14 were utilised.

Bar	Setting
Front	480 dtex Dorlastan V500
2	480 dtex Dorlastan V500
3	Mono-filament PES 0.25mm
Rear	Mono-filament PES 0.15mm

Table 14

Other parameters were set to standard values according to the machine running conditions.

After manufacture the fabric was heat set for 1 minute at 100°C.

Figure 33 shows photographs of the front and back of the knitted fabric produced using the stitch pattern of Figure 28 and the settings of Tables 13 and 14.

Figure 34 shows a further variation of a stitch pattern for knitting an auxetic fabric. This pattern is a variation on that shown in Figure 23 with a Tricot stitch being used for Guide Bar 2. The fibres described in relation to Figure 23 may be utilised with this stitch pattern.

The fabric was tested by applying a tensile strain at approximately 45 degrees to the warp direction and monitoring the width of the fabric. It was observed that as the fabric extended in length, its width increased, clearly demonstrating auxetic behaviour.

It has therefore been demonstrated how to manufacture a knitted fabric having a negative Poisson's ratio in at least one direction. As explained previously, the knitted fabrics disclosed herein comprise an auxetic component and a stabilising component. The auxetic component comprises shapes that provide an auxetic behaviour and are formed of fibres that are of a relatively higher modulus than the fibres of the stabilising component. The stabilising component acts to restore the auxetic component to its resting shape after the fabric has been deformed. The fabric can therefore return to its original shape and provide auxetic behaviour on subsequent stretchings. The material disclosed herein is not therefore a 'single shot' material but may find applications where the continued performance is required. However, as will be appreciated by the skilled person, a fabric could be knitted using only the auxetic component described herein to provide a one-shot fabric. Such fabrics may find application where no repeat performance is required. Modification of the knitting patterns described herein may be required to produce such one-shot fabrics.

The behaviour of the fabric is defined by the interaction and relative characteristics of the stabilising and auxetic components of the fabric. The changes in the knit patterns between the example fabrics described herein affect those relative characteristics and as demonstrated by the measurements this affects the performance of the fabrics.

A general trend from the first to fourth patterns are an increase in the modulus of the stabilising component. Pattern four also introduces a lateral interaction of the stabilising component with the auxetic component pattern for the red stabilising fibre such that it

acts to pull the centre of the re-entrant side of the triangles out of the triangle, thereby acting to expand the fabric in the lateral direction. It is thought this may contribute to the improved negative Poisson's ratio seen for this fabric.

As will be appreciated, the fabrics described herein are solid fabrics, as contrasted to net fabrics, which are significantly different types of material. Net fabrics have large open spaces between stitches to create a net structure, whereas the fabrics described herein only have minor open spaces within the stitches forming the fabric. In net fabrics open spaces are bounded by stitches of the fabric, whereas in the current fabrics any open spaces are bounded by straight yarns. Net fabrics are generally formed of tricot course and chain courses in which the yarn stitches meander across the fabric to create the open spaces that characterise a net fabric in contrast to the solid fabrics described by the current invention. A detailed discussion of net fabrics and their characteristics can be found in Chapter 26 of "Knitting Technology: A Comprehensive Handbook and practical guide" by David J Spencer. From that description it is immediately apparent that the currently described fabrics are not net fabrics.

Described below are various extensions of the principles applied above to knitted fabrics.

More generally than noted above, Figure 2 shows a schematic diagram of an auxetic structure comprising a reinforcement component as described in relation to Figure 1, and a recovery component. The reinforcement and recovery components are joined at the vertices of the reinforcement shape at which they coincide. The recovery component therefore acts to pull the base of the arrowhead shape together. As a strain is applied vertically to the material, the arrowheads expand as shown in Figure 3, and the recovery component is stretched. When that strain is removed the recovery components are exerting a force across the base of the arrowheads which acts to return the structure to the form shown in Figure 2. A structure which returns to its original shape, and displays repeated auxetic behaviour is therefore provided by the structure shown in Figure 2.

The structure of Figure 2 operates due to the combination of a high modulus reinforcement component having auxetic properties in conjunction with an elastic, low modulus, recovery component. The reinforcement component provides the negative Poisson's ratio when a strain is applied and the recovery component returns the reinforcement component back to its original shape upon removal of the deforming strain. This principle can be applied to a range of auxetic structures as shown schematically in Figure 5.

The reinforcement and recovery components may be provided using any suitable materials and may be formed using any suitable manufacturing techniques. A number of examples of sheet materials will now be described which embody the principles set out above.

The materials forming the auxetic component and their recovery component are not necessarily fibres, but may be any suitable materials providing the required mechanical properties. For example, the recovery component may be a matrix component into which the auxetic component is embedded.

A description of the manufacture of a knitted auxetic fabric is provided later in this description.

In a first example of the invention, an auxetic knitted fabric may be embedded in a neoprene matrix to form a composite material. The neoprene matrix may be formed to completely enclose the knitted structure, or the knitted structure may be on the surface of the neoprene. Neoprene is used as an example only and any comparable material may be utilised for the matrix component as dictated by the requirements of the resulting material.

In a second example, which may be particularly useful in armour applications, the auxetic component is formed from carbon fibre and the recovery component is formed from a low modulus fibre such as aramid or polyethylene.

In a third example, the auxetic component is provided by a fibre or monofilament stitched to an elastic sheet which provides the recovery component. The vertices at either end of the re-entrant side of the auxetic component are fixed to the recovery element. A sewing machine may be used to form the auxetic component on the elastic sheet, or for a thicker or harder recovery element holes may be pre drilled and the auxetic element threaded through the holes. Furthermore, the auxetic component may be stapled or bonded to the recovery component. The auxetic component may be formed by etching a metallic element pre-laminated on the recovery component. A suitable material for the recovery component may be a neoprene sheet.

In a fourth example, which may be particularly useful for armour, the auxetic component is provided by a carbon fibre, stitched to a substrate made from a commercially available

composite material such as that made from aramid fibres in an elastomeric resin matrix, so that the vertices at either end of the re-entrant side of the auxetic component are fixed to the recovery element. The auxetic component may be created on a thin sheet of laminate and then embedded in further layers of laminate to create a thicker sheet. Several layers of the auxetic component may be produced and embedded between further layers of the recovery element to form a multi layer laminated structure.

In a fifth example, the auxetic component may be formed using a fibre placement and bonding technique, and the recovery component is bonded to the vertices as described above.

In a sixth example, the auxetic component may be cut or fabricated from sheet material, for example a thin sheet of steel. The recovery component may comprise a crimped wire mesh which is bonded or stitched to the vertices of the auxetic component.

In a seventh example, the auxetic component is a honeycomb material and the recovery component is an elastic component joining the vertices of the cells. For example, the honeycomb may be cut from a sheet material or extruded through a die. The recovery component may be elastic fibres joining vertices or may be a sheet bonded to the honeycomb. The sheet material and/or honeycomb may have a significant thickness. The vertices of the auxetic component may be formed as flexible sections of the component, or may be formed as specific hinge elements. The components may therefore be formed of a plurality of discrete components joined into the overall structure.

The recovery component may also be provided by the auxetic component. For example, the auxetic component may deform by hinging at the vertices, as shown in Figures 1 and 2. Those vertices may be made such that the deformation towards Figure 2 is elastic and thus when the strain is removed the auxetic component has internal forces which attempt to return it to the undeformed state. Similarly, deformation may occur by rib flexing. Elastic flexing may be utilised to provide the recovery force to return the auxetic component to the undeformed state.

In an eighth example the auxetic component and recovery component are formed as one component, the action of the recovery component being provided by elastic deformation of the component. For example, there may be elastic deformation at the rib hinges, or of the ribs.

The scale of these example materials may be tailored to the specific example for which they are to be utilised and the materials and techniques used to manufacture them. For example, the unit cells may be comparable to the size provided by the knitted fabrics or may be significantly smaller or larger. The thickness of the sheet material is defined by the materials from which the sheet is manufactured and it is not envisaged that all examples will be thin as per the fabrics, but thicker sheets are explicitly contemplated where this is appropriate for the materials and manufacturing techniques.

As has been explained previously the properties of the materials described herein are dependent on the relative properties of the materials forming the materials. Various deformation mechanisms have been described, for example rib flexing, rotation and stretching. The selected materials will define the mode of deformation and hence the properties of the resulting sheet material.

Any of the features of the examples described above may be combined as appropriate to provide a material having the required properties.

Either element may be formed using a smart material such as material having a high expansion coefficient or be an electrically activated material known as a piezoelectric.

There is therefore described an auxetic sheet material, comprising an auxetic component formed from a first material, and a recovery component formed from a second material, wherein the first and second materials have different mechanical properties, wherein the auxetic sheet material is not exclusively an auxetic knitted fabric, comprising an auxetic component knitted from at least a first type of fibre, and a stabilising component knitted from at least a second type of fibre, wherein the first and second fibre types have different mechanical properties.

It will be understood that the benefits and advantages described above may relate to one embodiment or may relate to several embodiments. It will further be understood that reference to 'an' item refers to one or more of those items.

The steps of the methods described herein may be carried out in any suitable order, or simultaneously where appropriate. Additionally, individual blocks may be deleted from any of the methods without departing from the spirit and scope of the subject matter described herein. Aspects of any of the examples described above may be combined

with aspects of any of the other examples described to form further examples without losing the effect sought.

It will be understood that the above description of a preferred embodiment is given by way of example only and that various modifications may be made by those skilled in the art. The above specification, examples and data provide a complete description of the structure and use of exemplary embodiments of the invention. Although various embodiments of the invention have been described above with a certain degree of particularity, or with reference to one or more individual embodiments, those skilled in the art could make numerous alterations to the disclosed embodiments without departing from the spirit or scope of this invention.

Claims

1. An auxetic solid knitted fabric, comprising
an auxetic component knitted from at least a first type of fibre, and
a stabilising component knitted from at least a second type of fibre, wherein
the first and second fibre types have different mechanical properties.
2. An auxetic fabric according to claim 1, wherein the first fibre type has a
substantially higher modulus of elasticity than the second fibre type.
3. An auxetic fabric according to claim 1, wherein the auxetic component comprises
a repeating pattern of auxetic elements.
4. An auxetic fabric according to claim 3, wherein each auxetic element is a re-
entrant triangle.
5. An auxetic fabric according to any preceding claim wherein the auxetic
component is knitted from two fibre types, the first fibre type and a third fibre.
6. An auxetic fabric according to any preceding claim wherein the stabilising
component is knitted from two fibre types, the second fibre type and a fourth fibre type.
7. An auxetic fabric according to any preceding claim knitted on a warp knitting
machine.
8. An auxetic fabric according to any preceding claim, wherein the stabilising
component acts to return the fabric to a stable state after deformation from the state by
application of strain to the fabric.
9. An auxetic fabric according to any preceding claim, wherein during expansion of
the fabric by an applied strain at least part of the fibres of the stabilising component
stretch elastically.
10. An auxetic fabric according to claim 9, wherein the fibres of the auxetic
component do not stretch during expansion.

11. An auxetic fabric according to any preceding claim, wherein a first phase of expansion of the fabric in response to an applied strain occurs by stretching of at least part of the stabilising component and deformation by hinging or bending of the auxetic component.

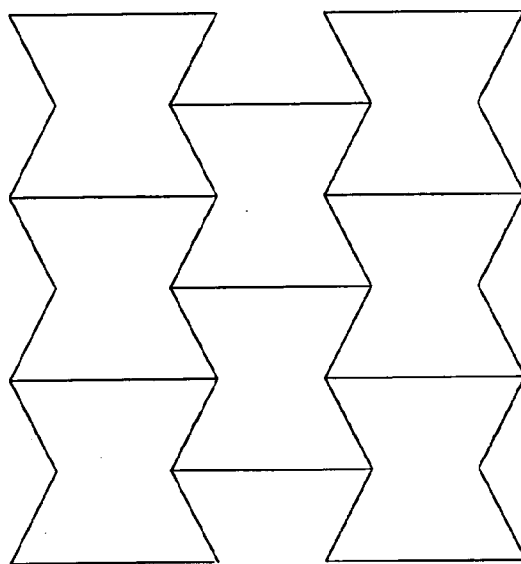
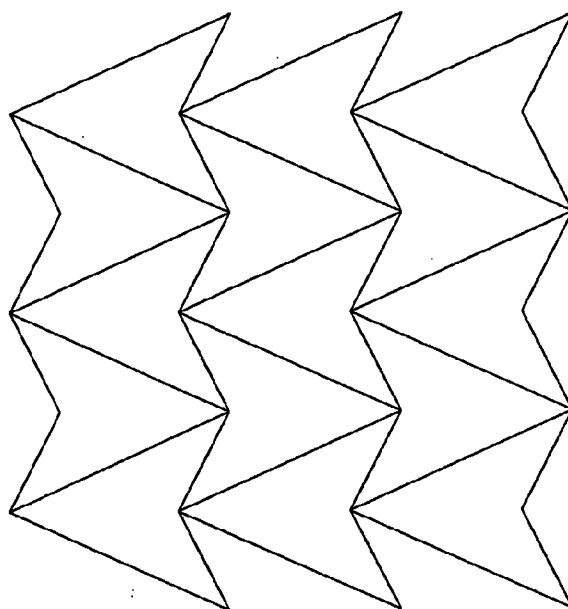


Figure 1

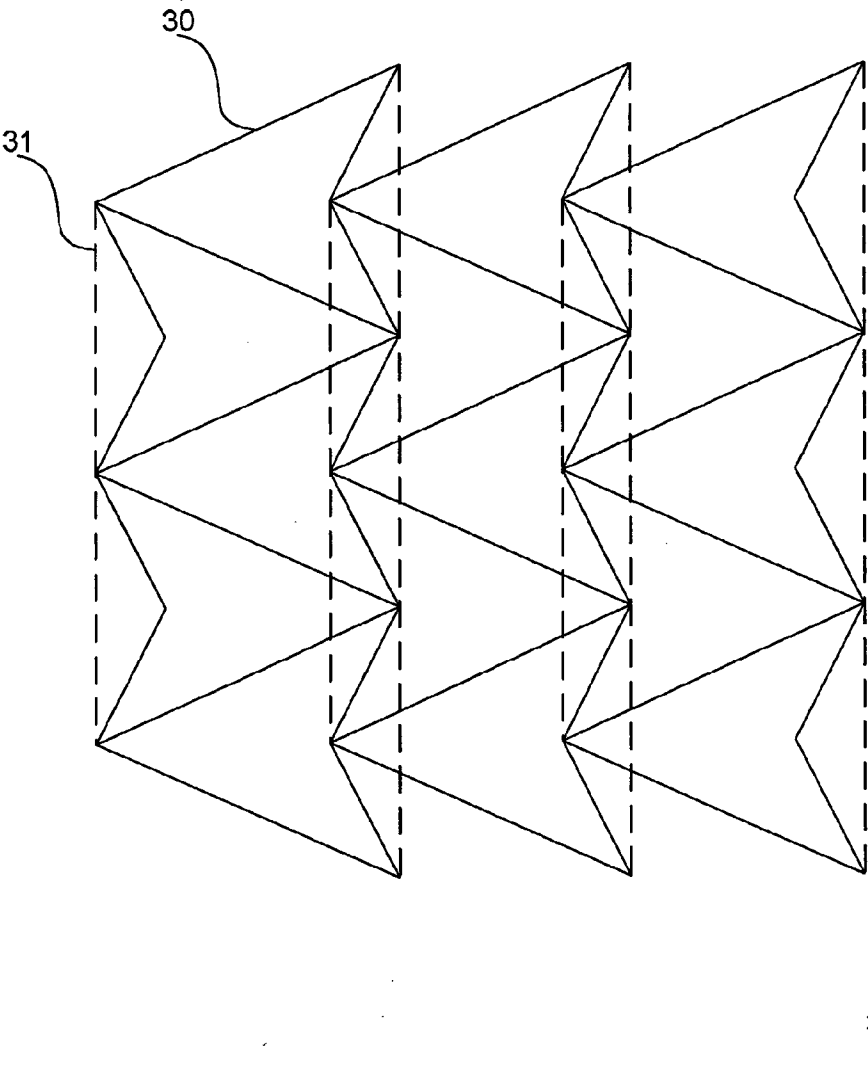


Figure 2

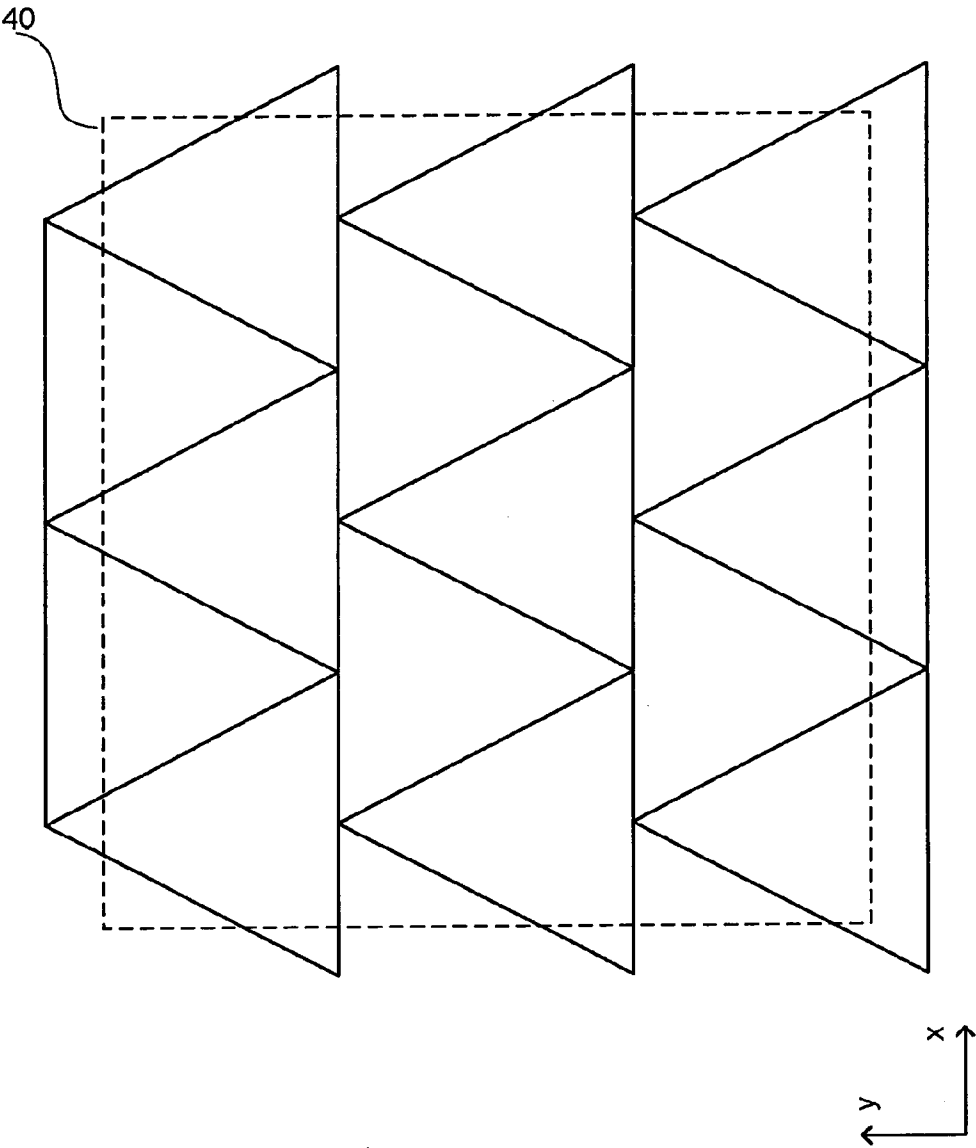


Figure 3

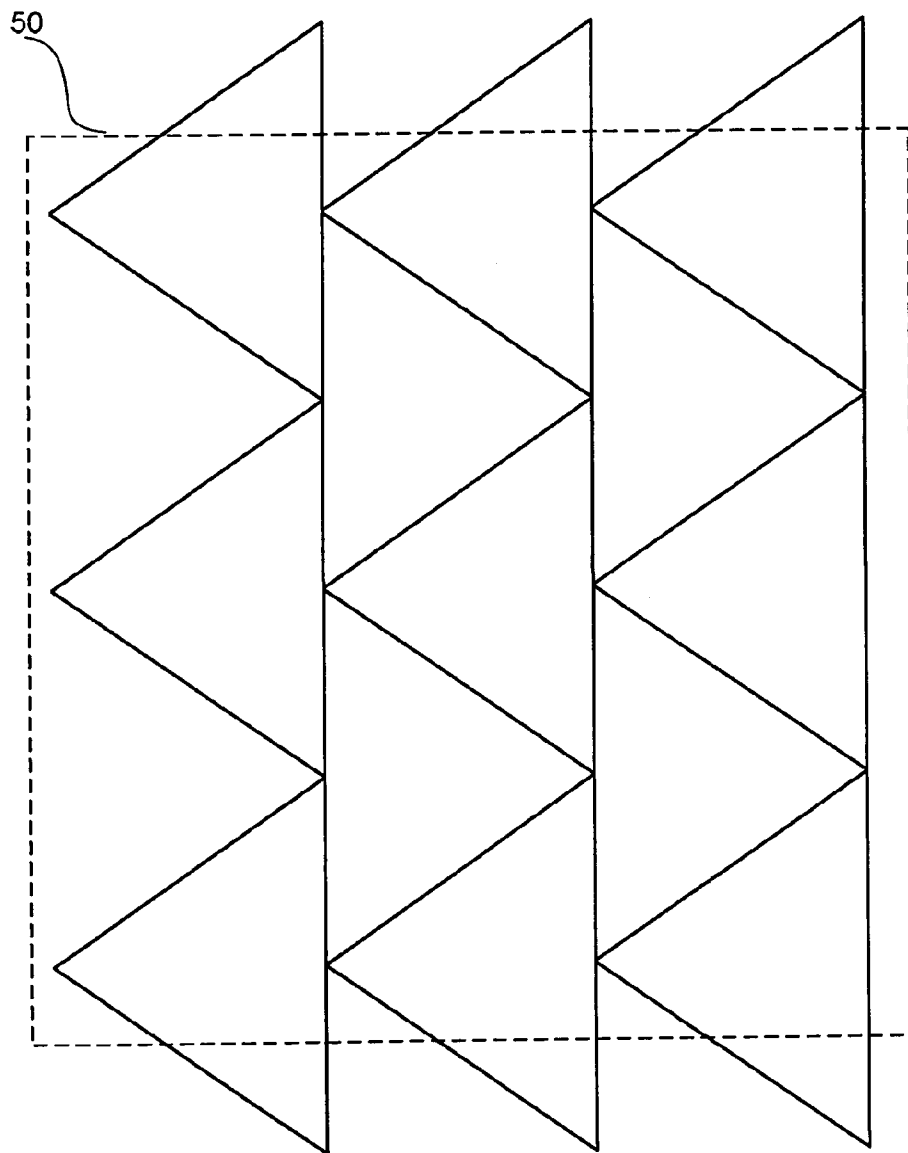


Figure 4

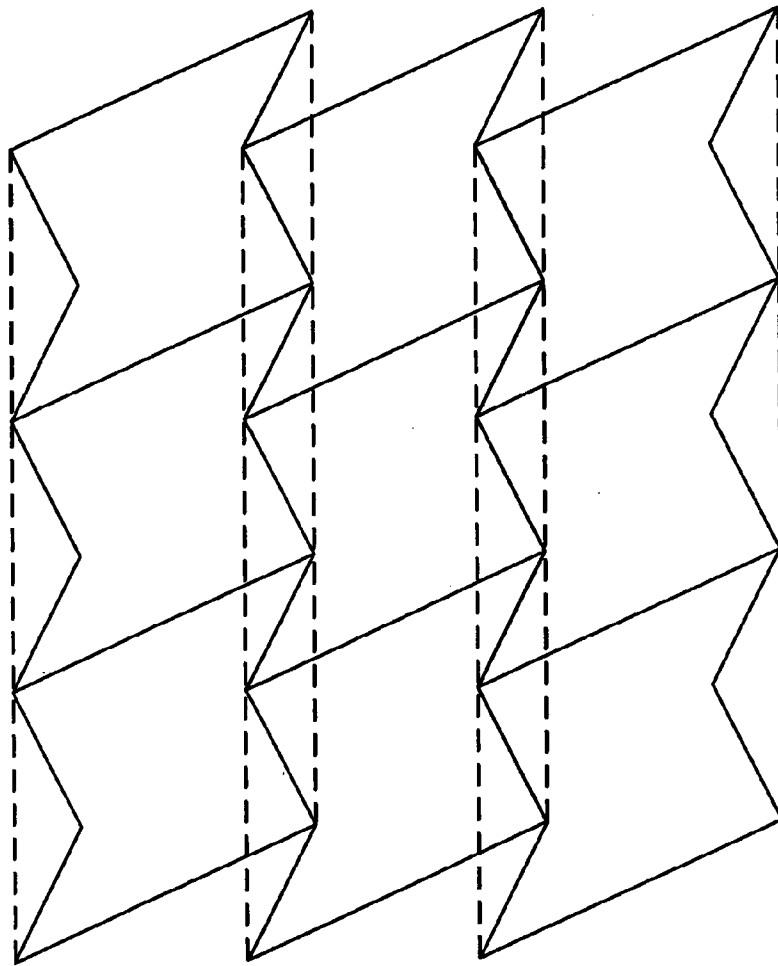


Figure 5

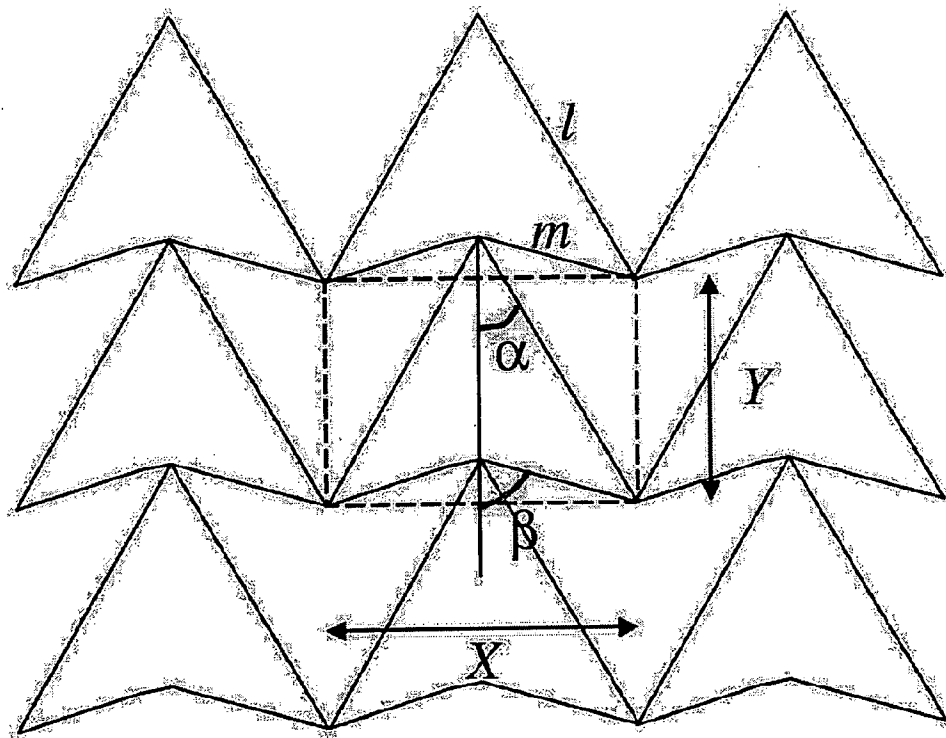


Figure 6

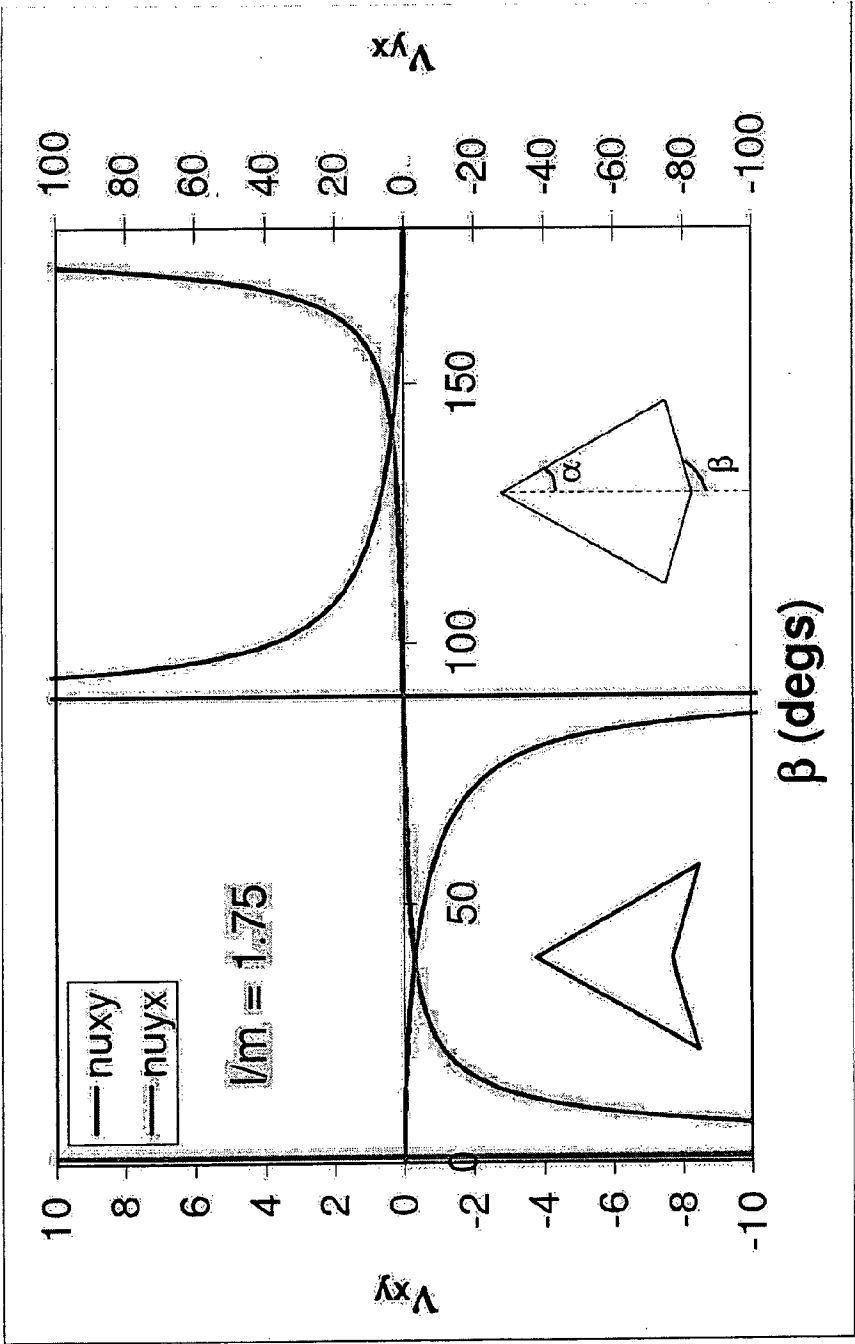


Figure 7

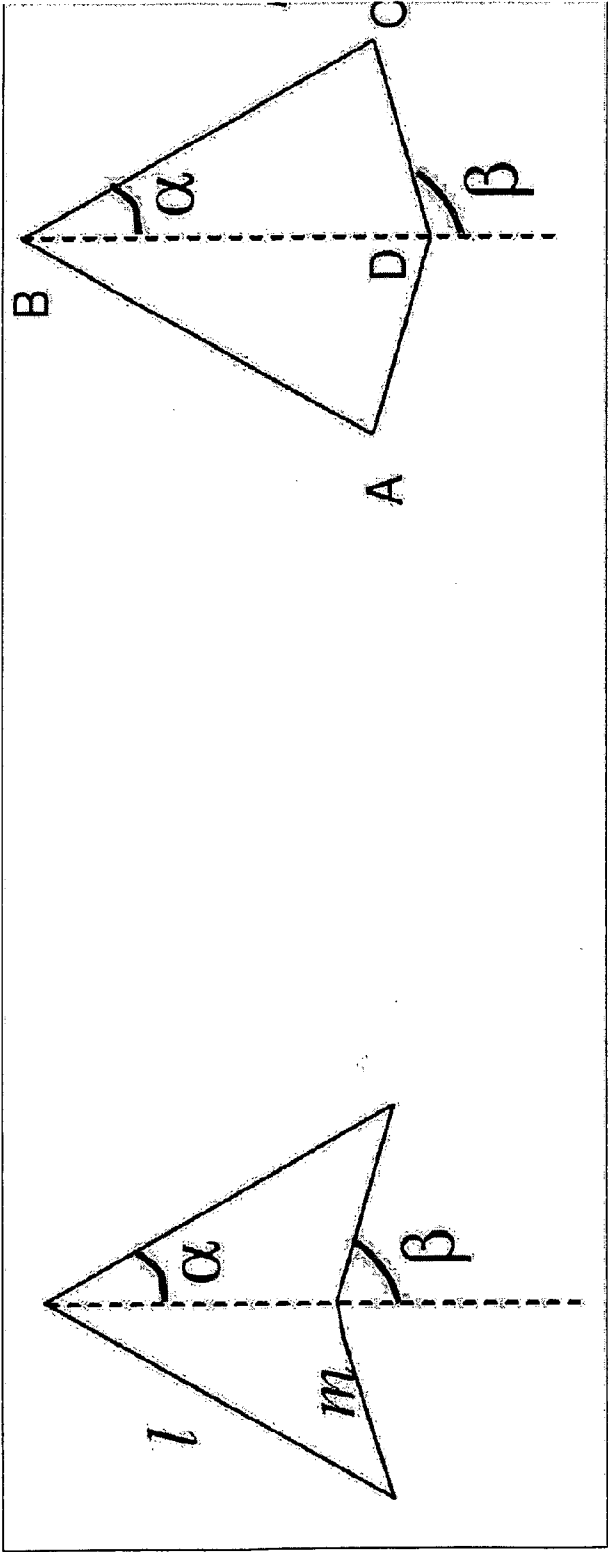


Figure 8

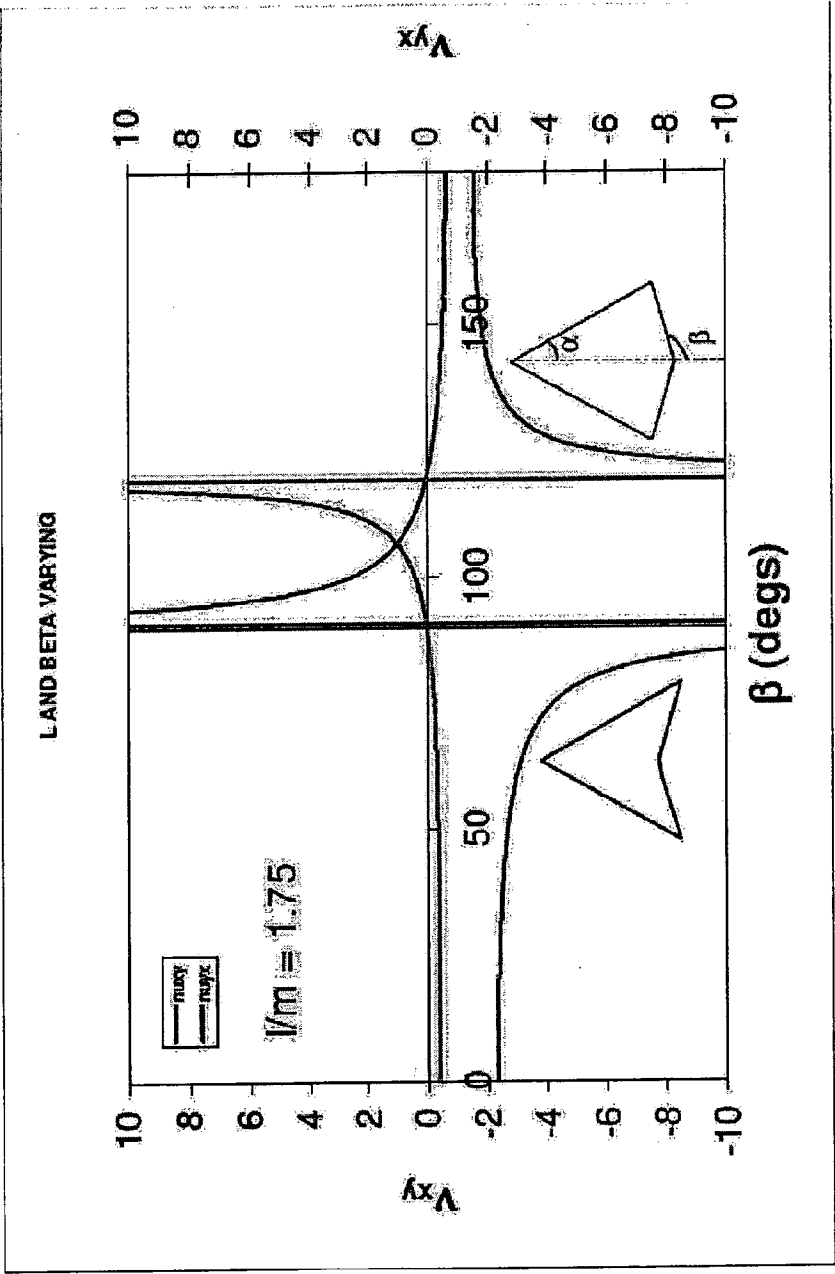


Figure 9

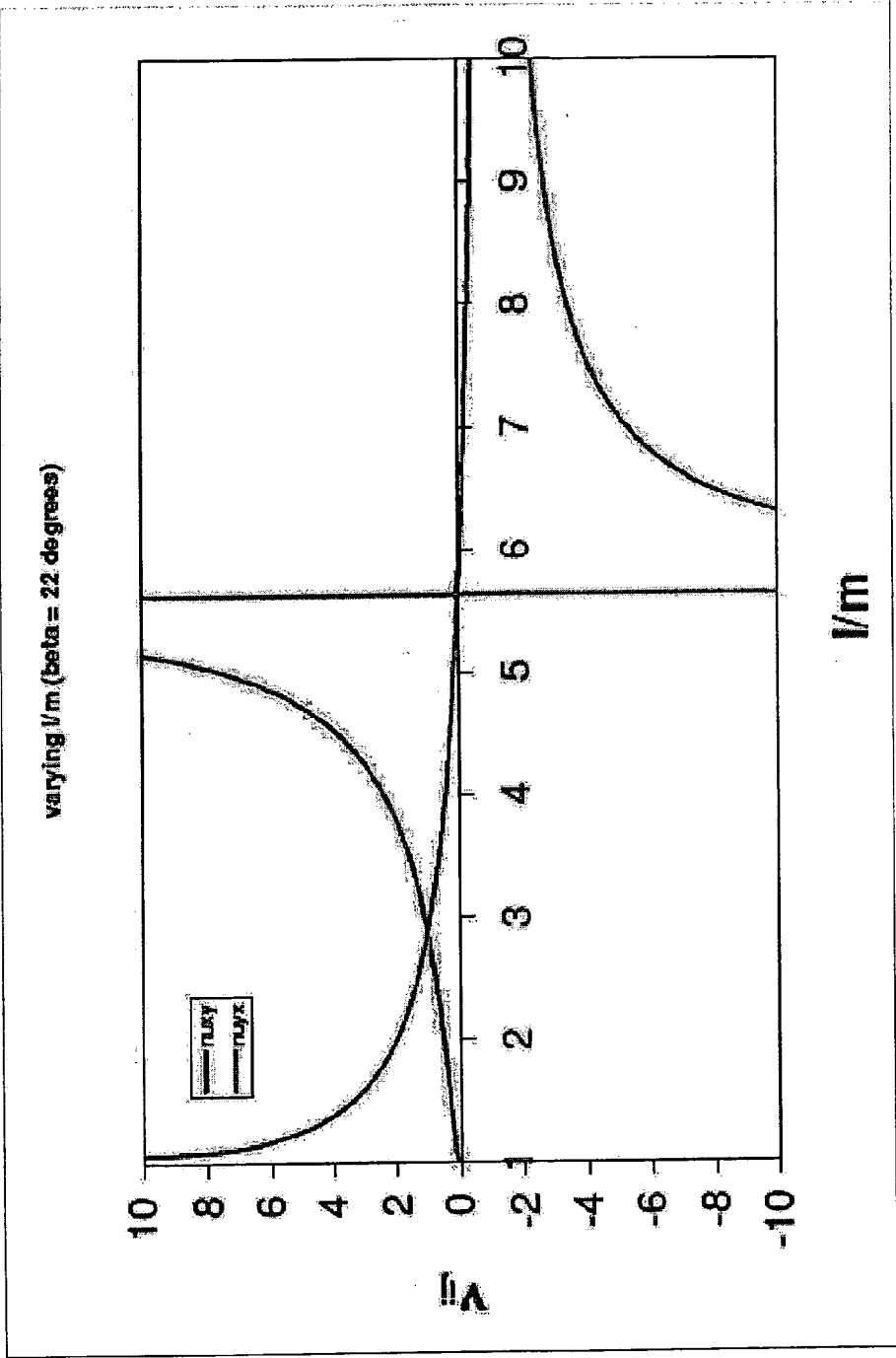


Figure 10

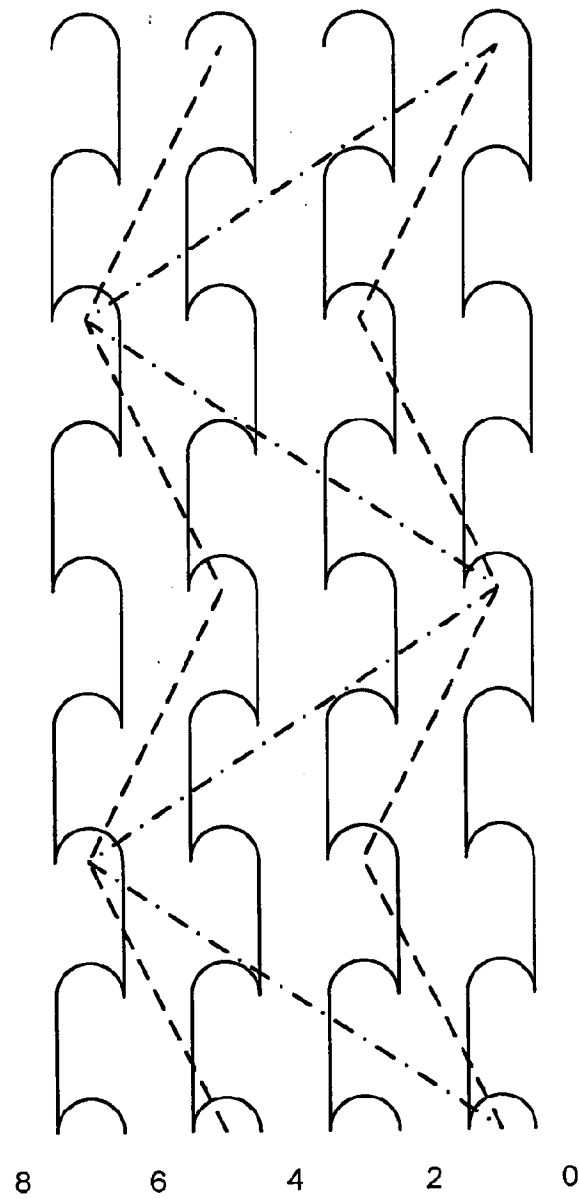


Figure 11

— Front guide bar
 - - - Middle guide bar
 - · - · - Back guide bar

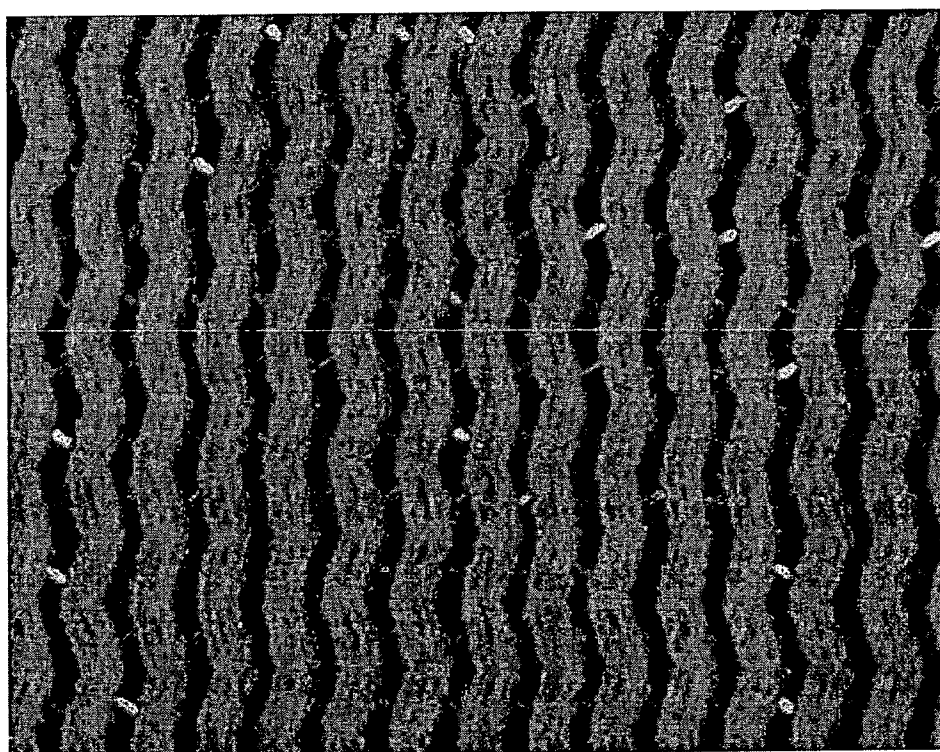


Figure 12

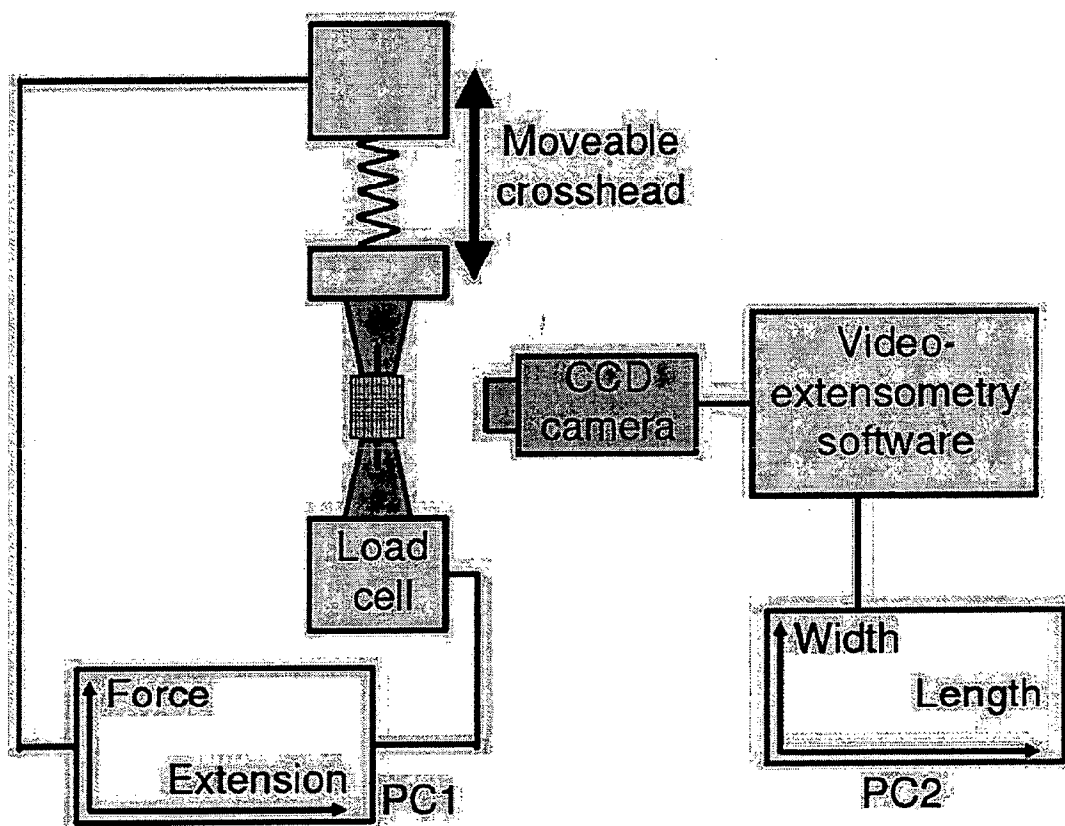


Figure 13

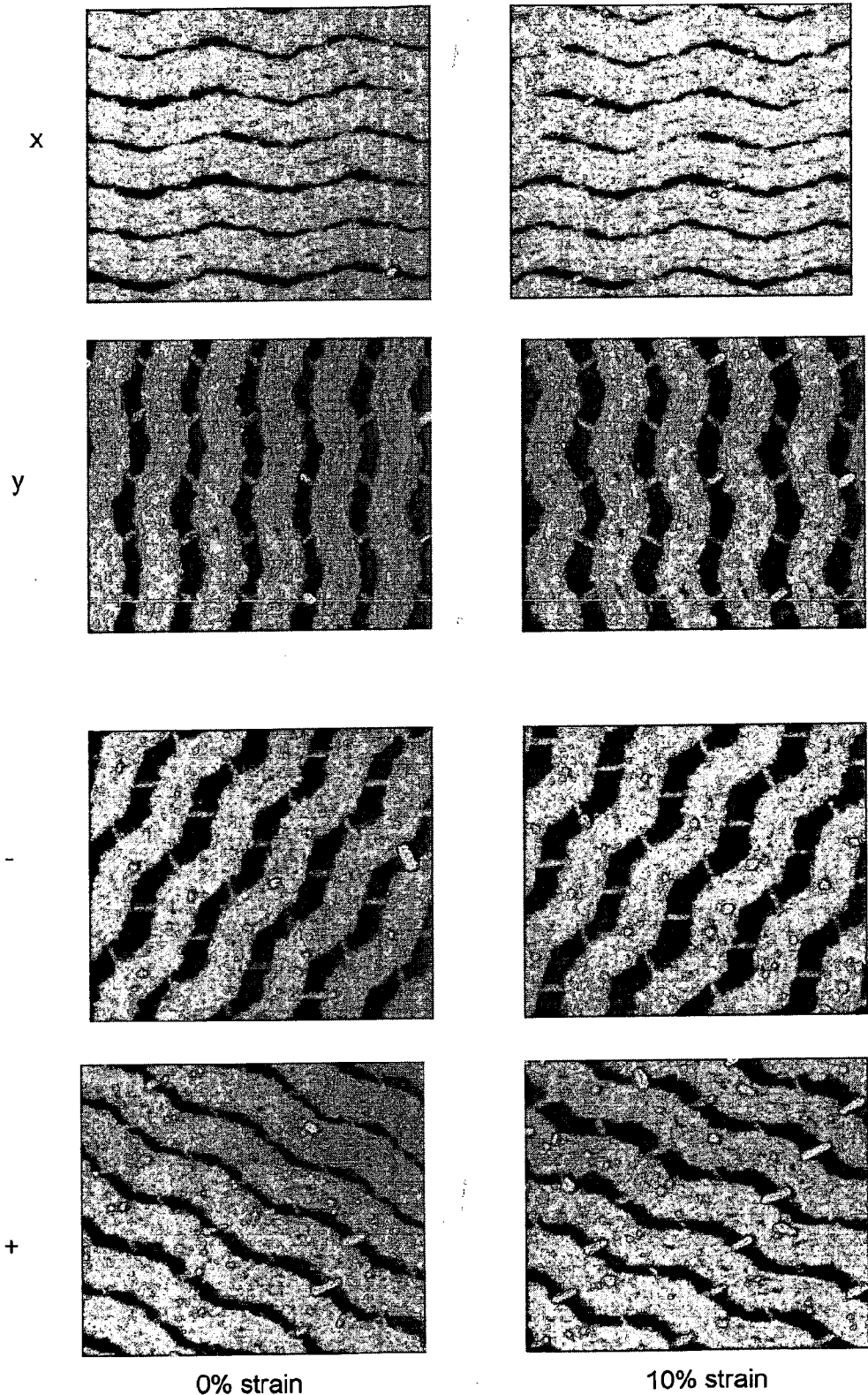


Figure 14

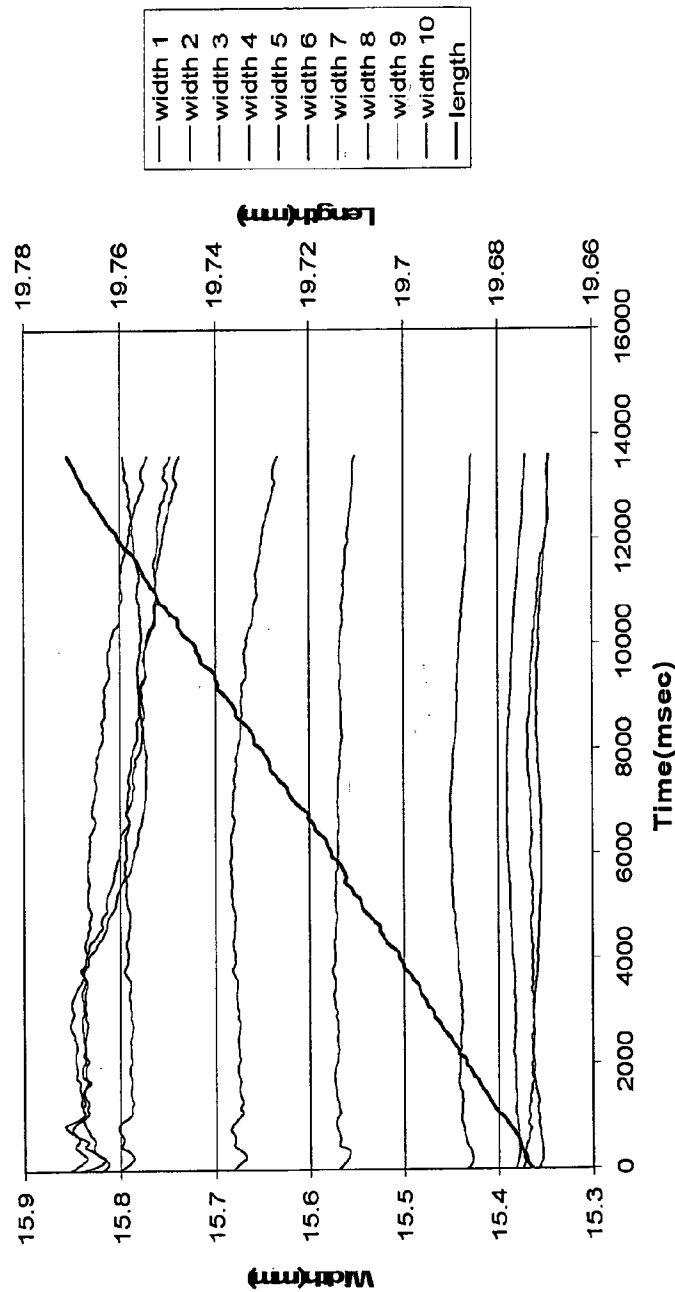


Figure 15a

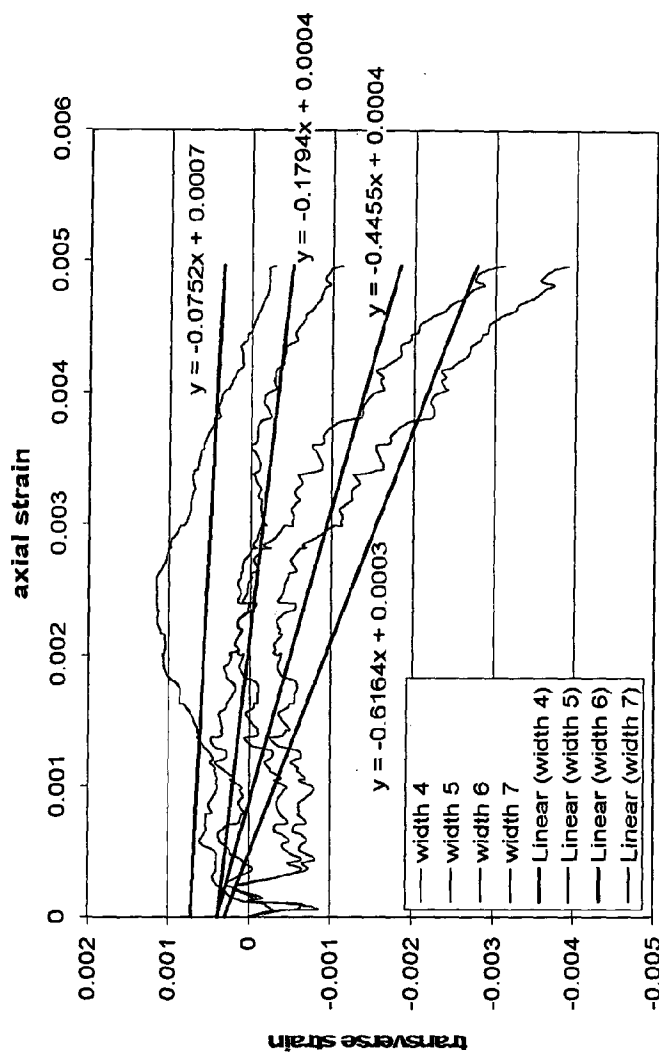


Figure 15b

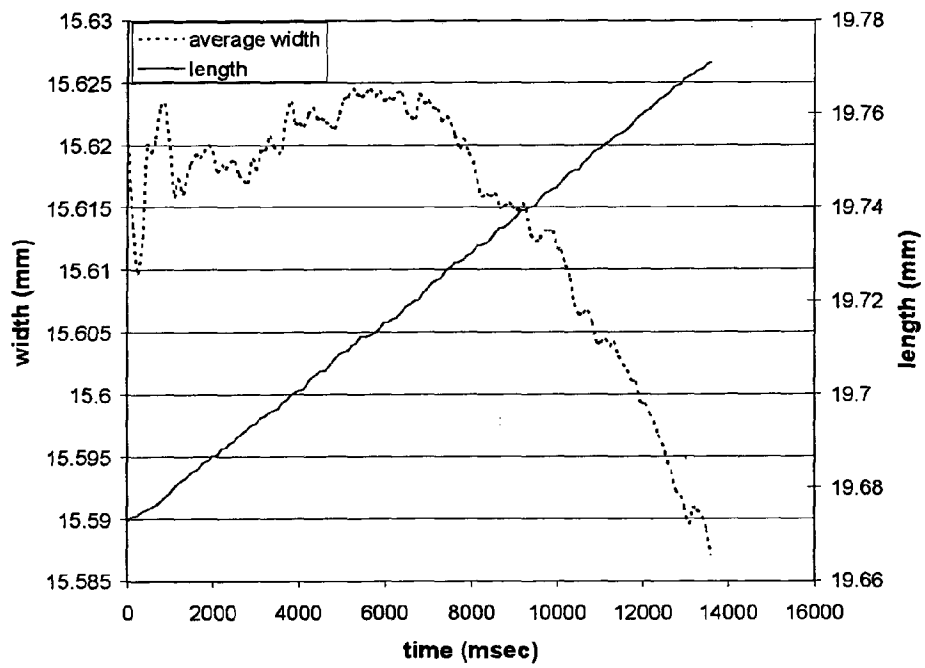
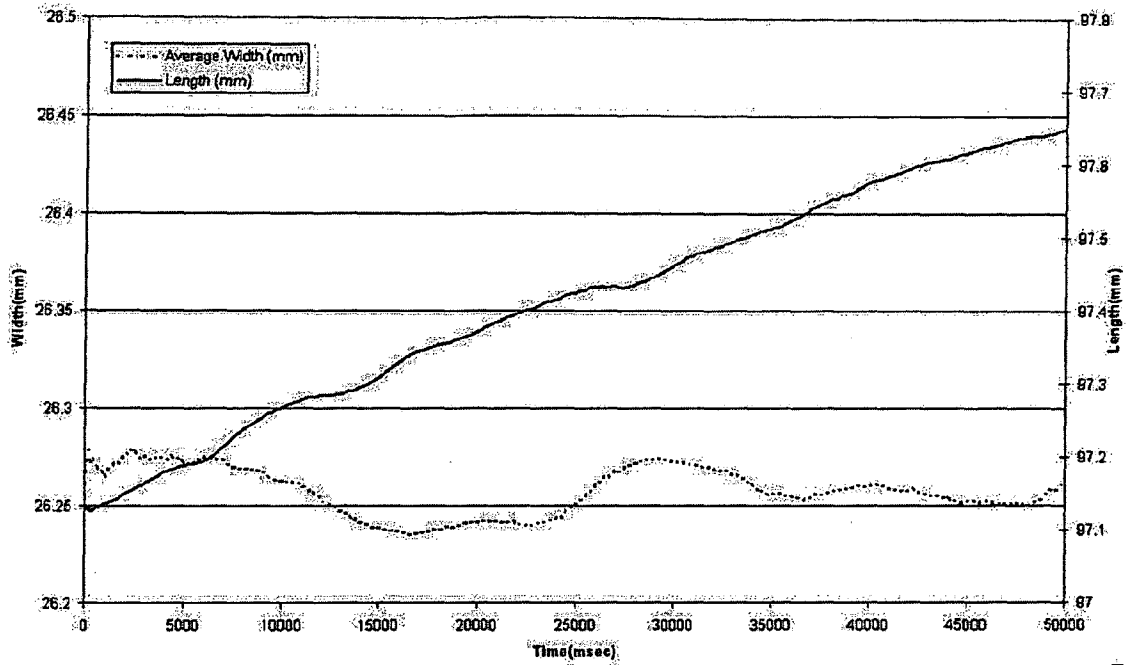


Figure 16a

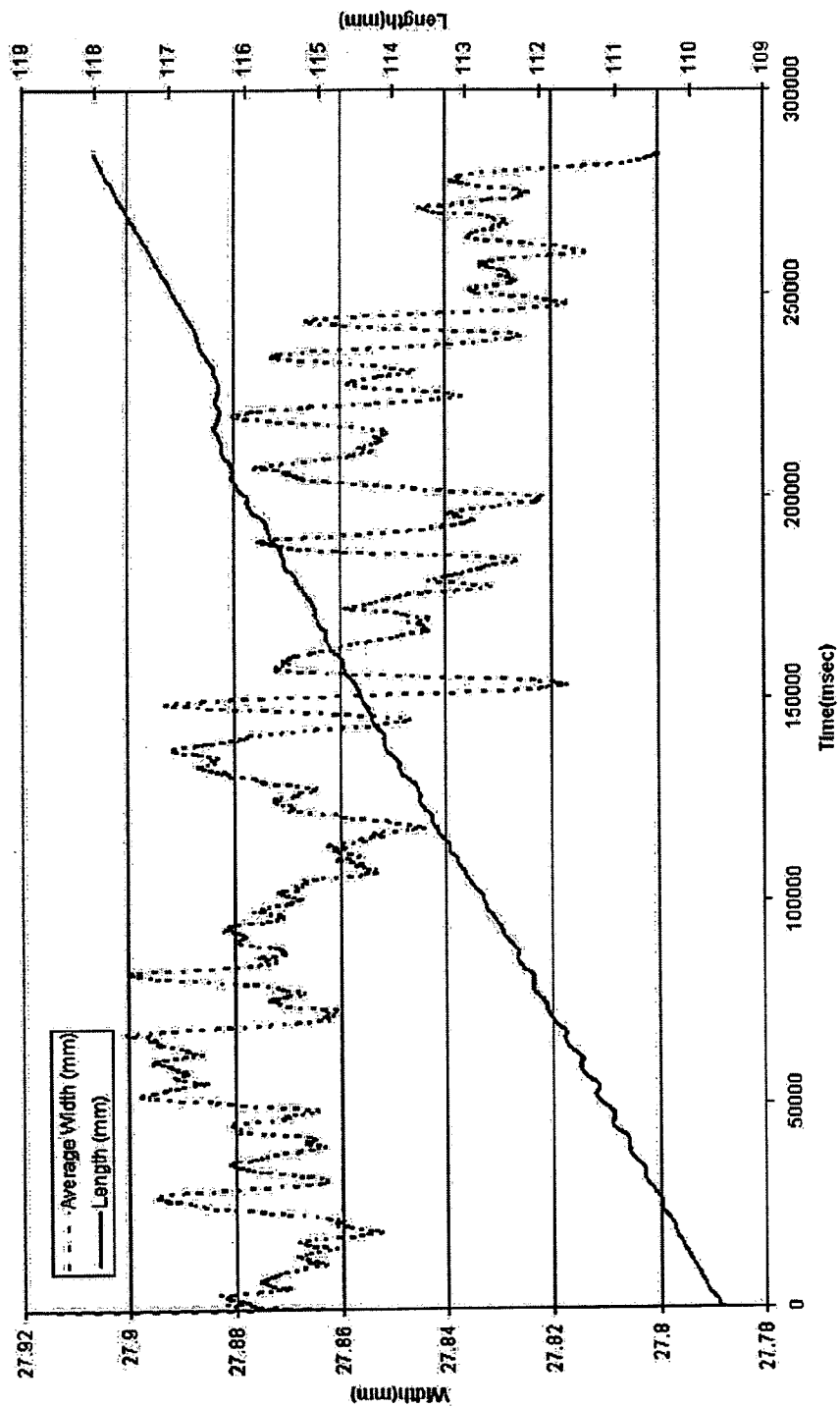


Figure 16b

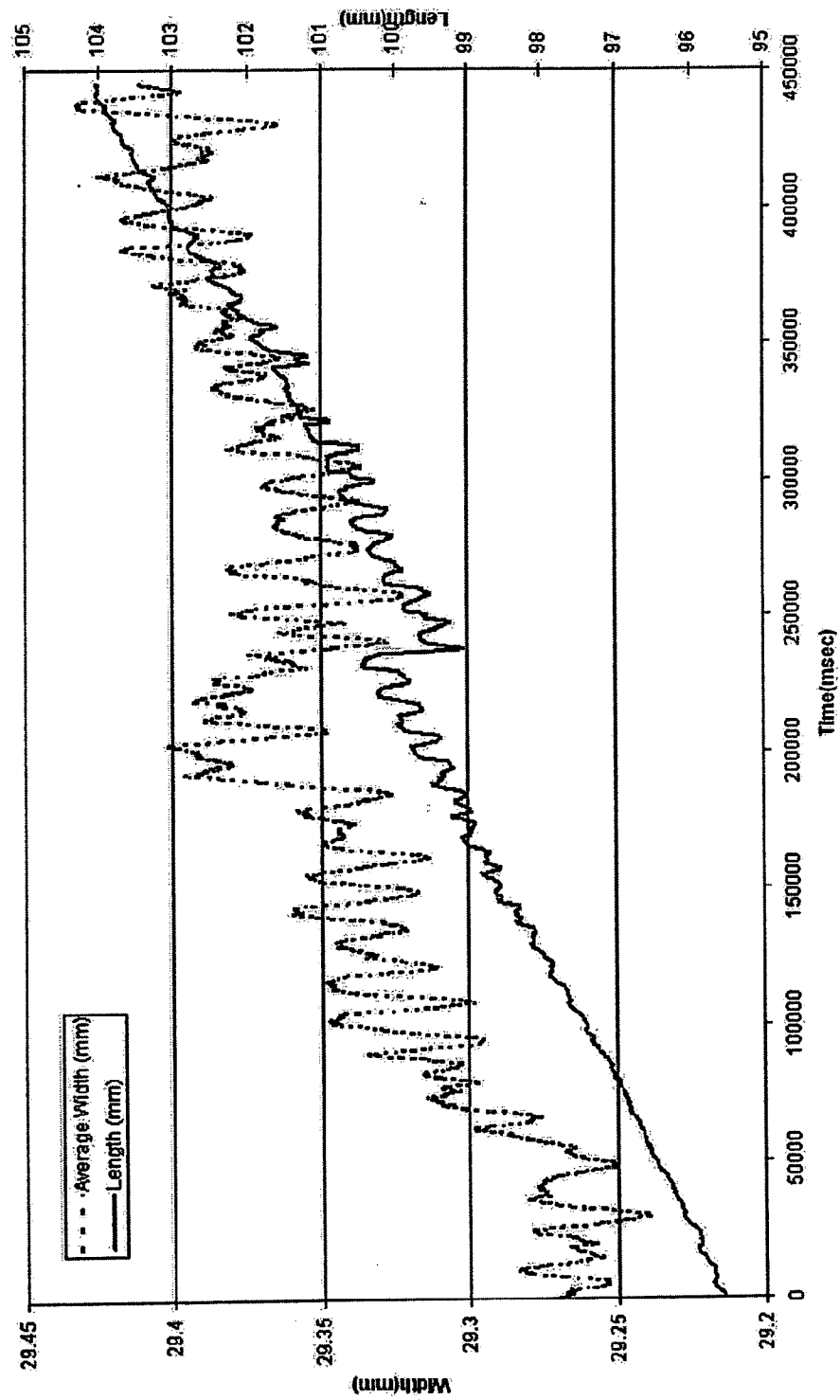


Figure 16c

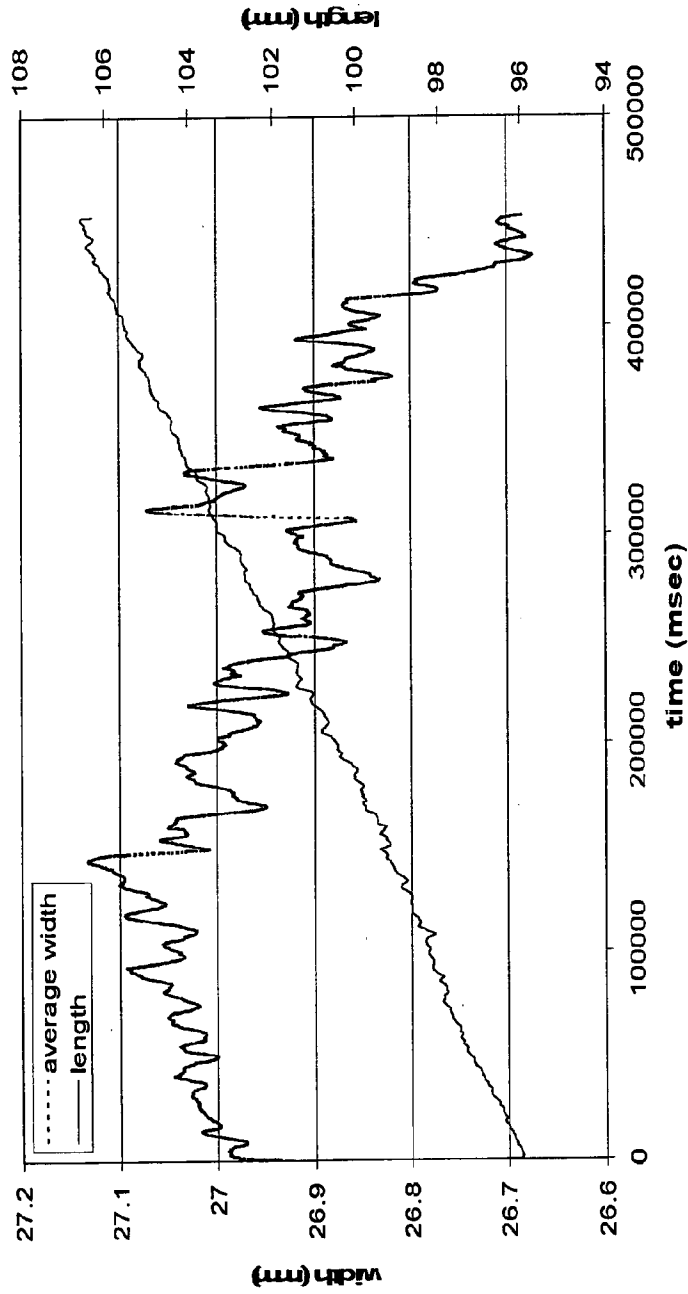


Figure 16d

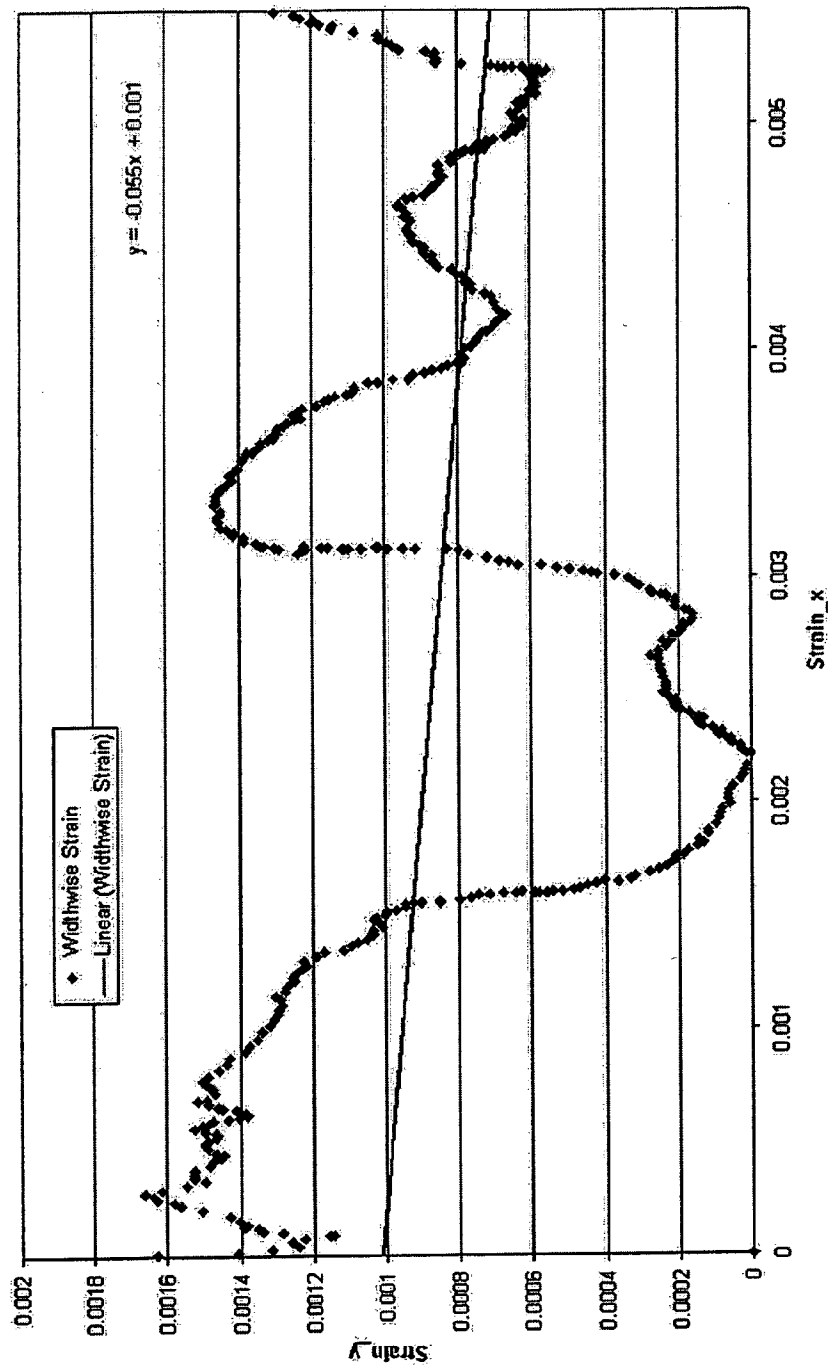


Figure 17a

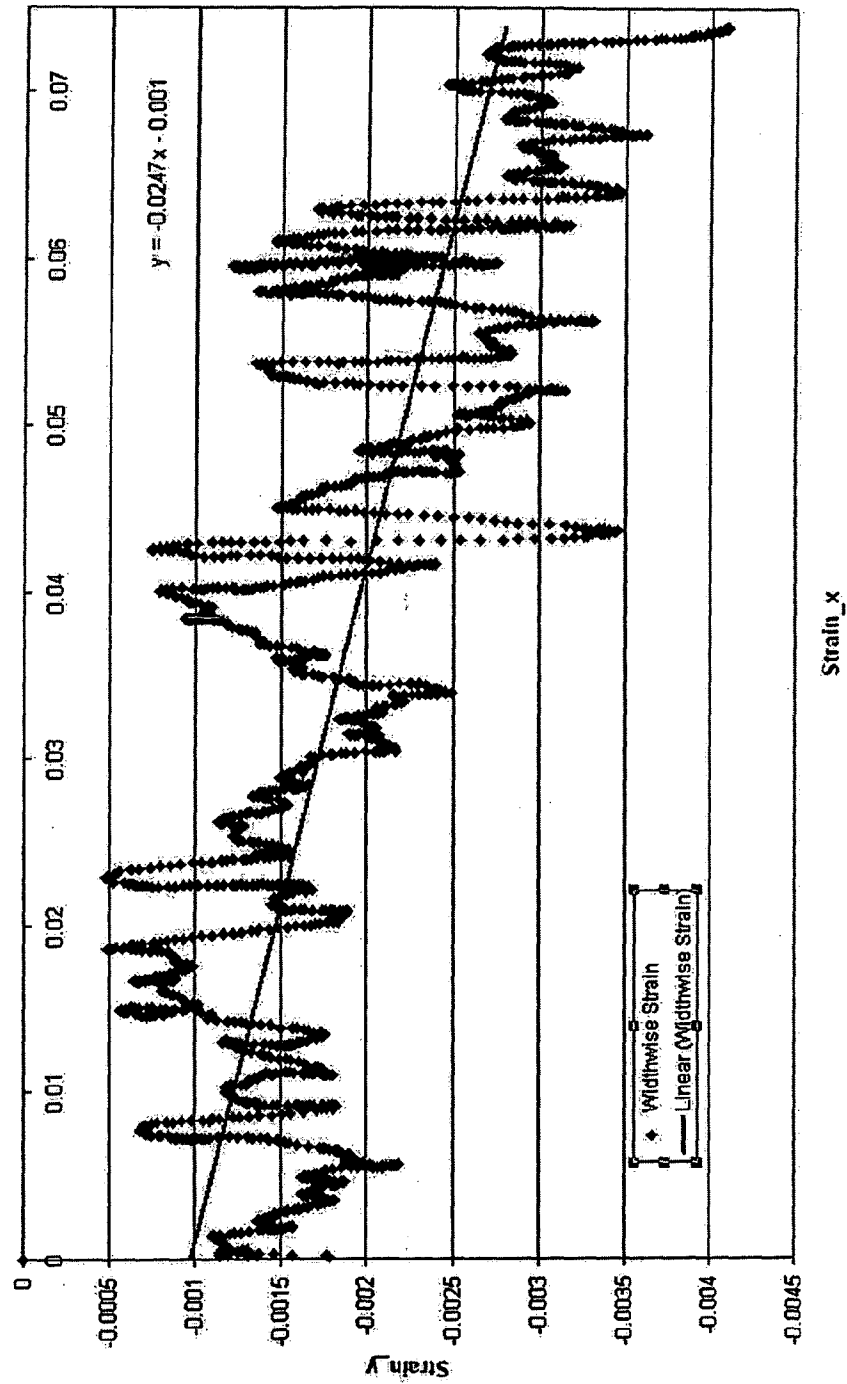


Figure 17b

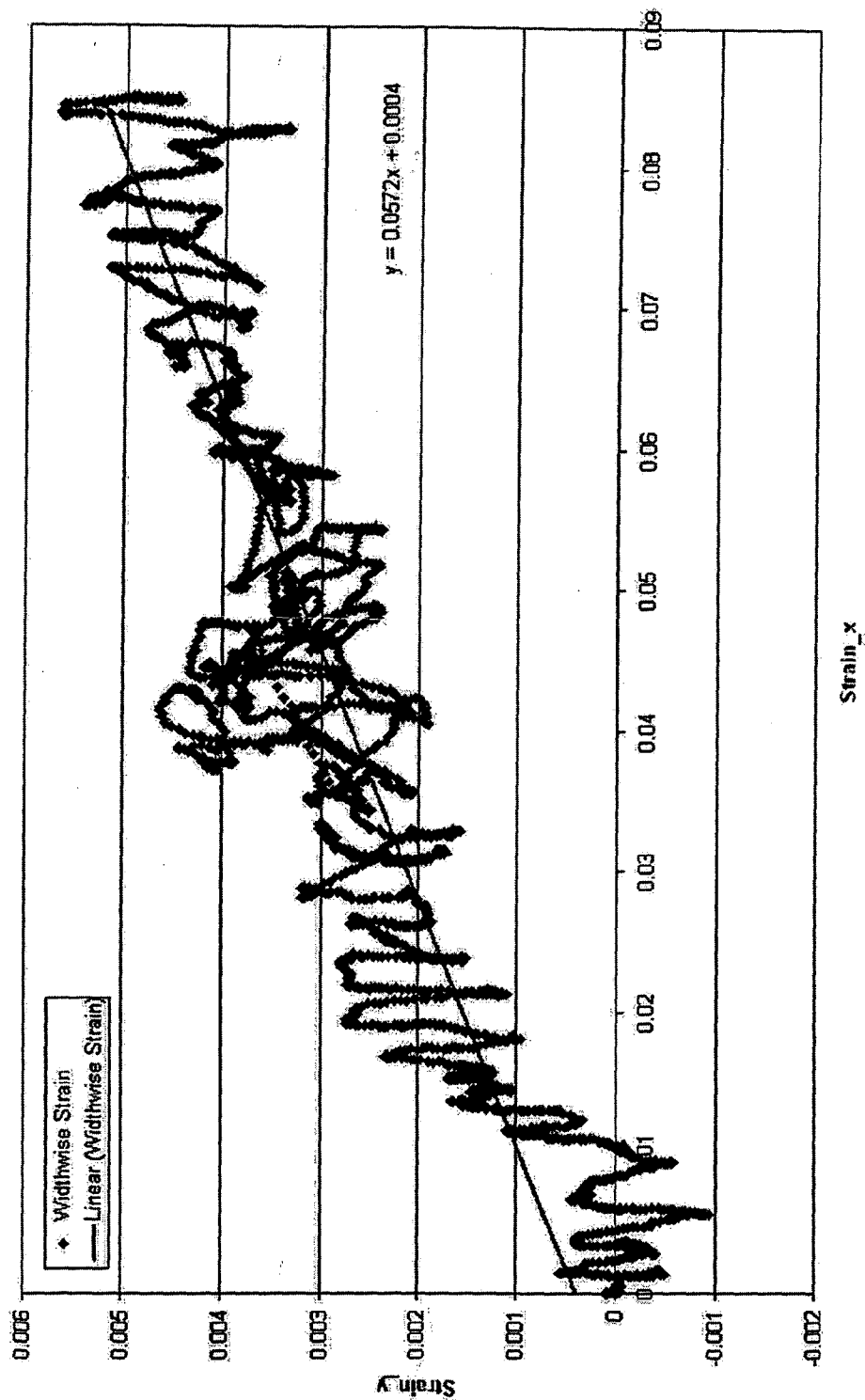


Figure 17c

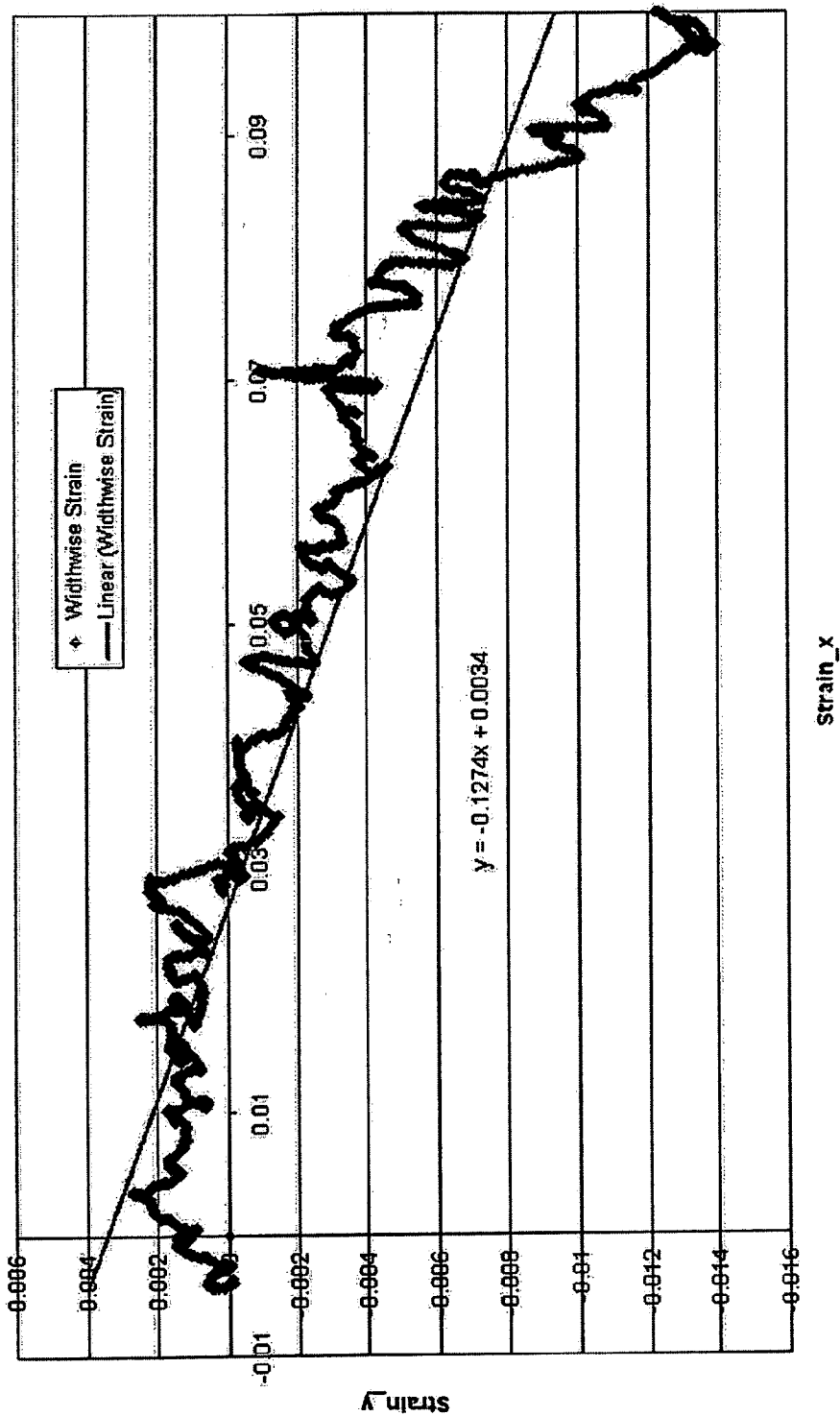
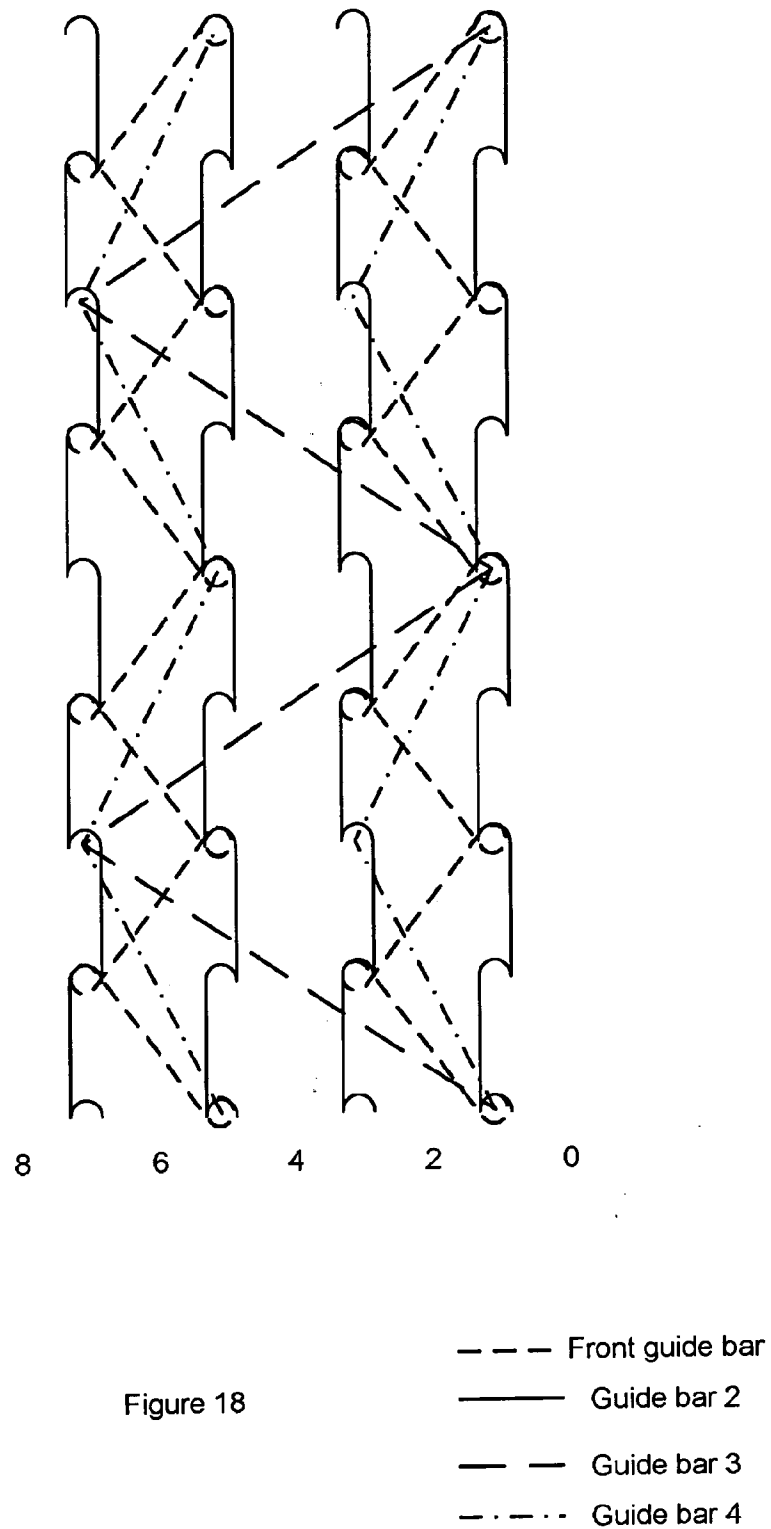


Figure 17d



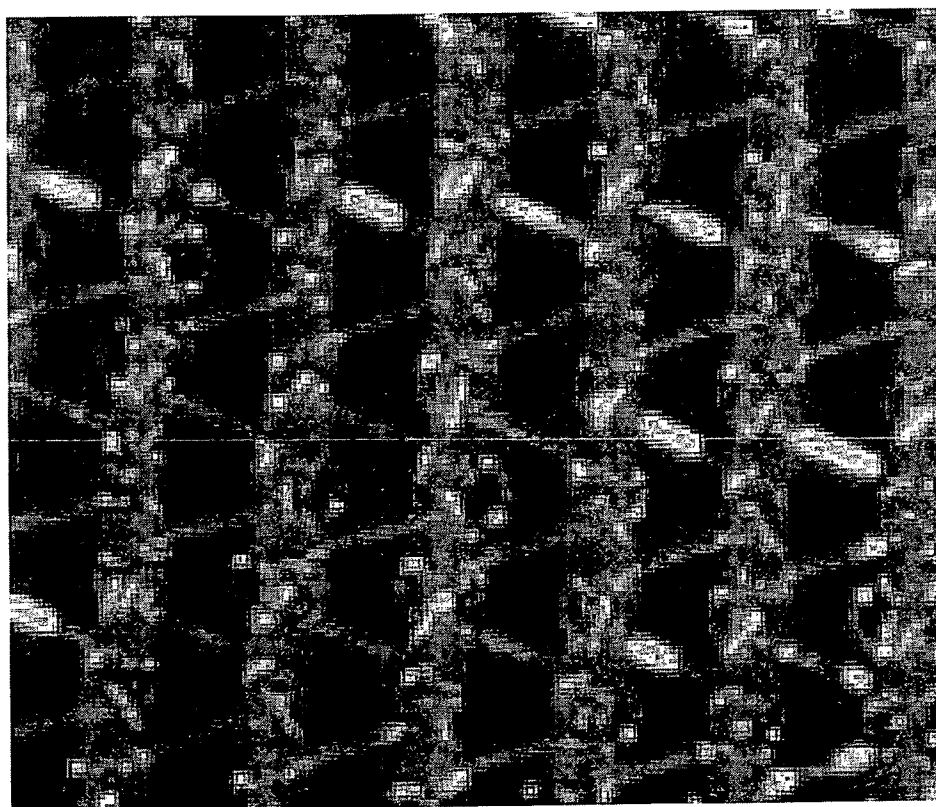
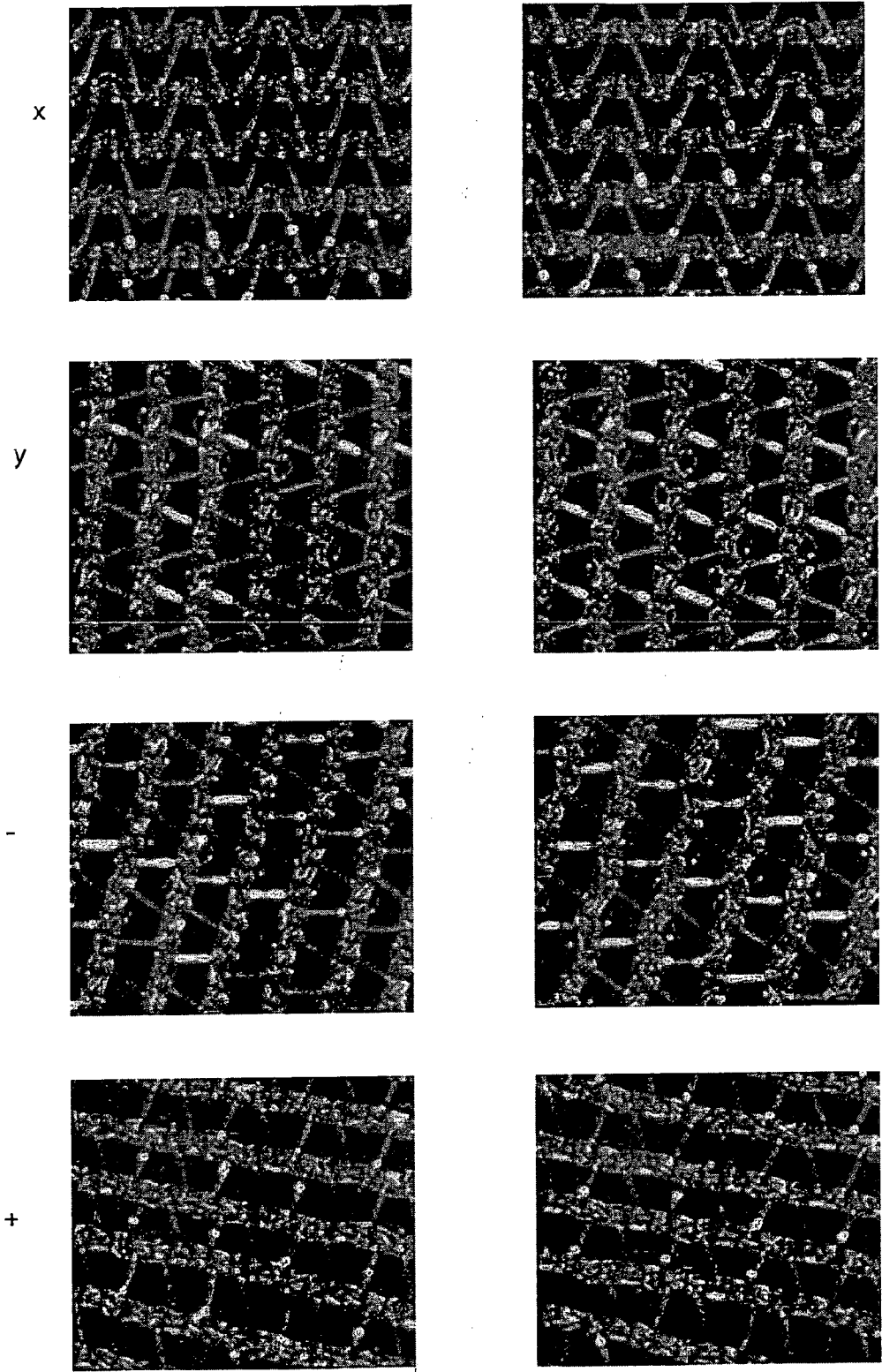


Figure 19



0% strain

Figure 20

10% strain

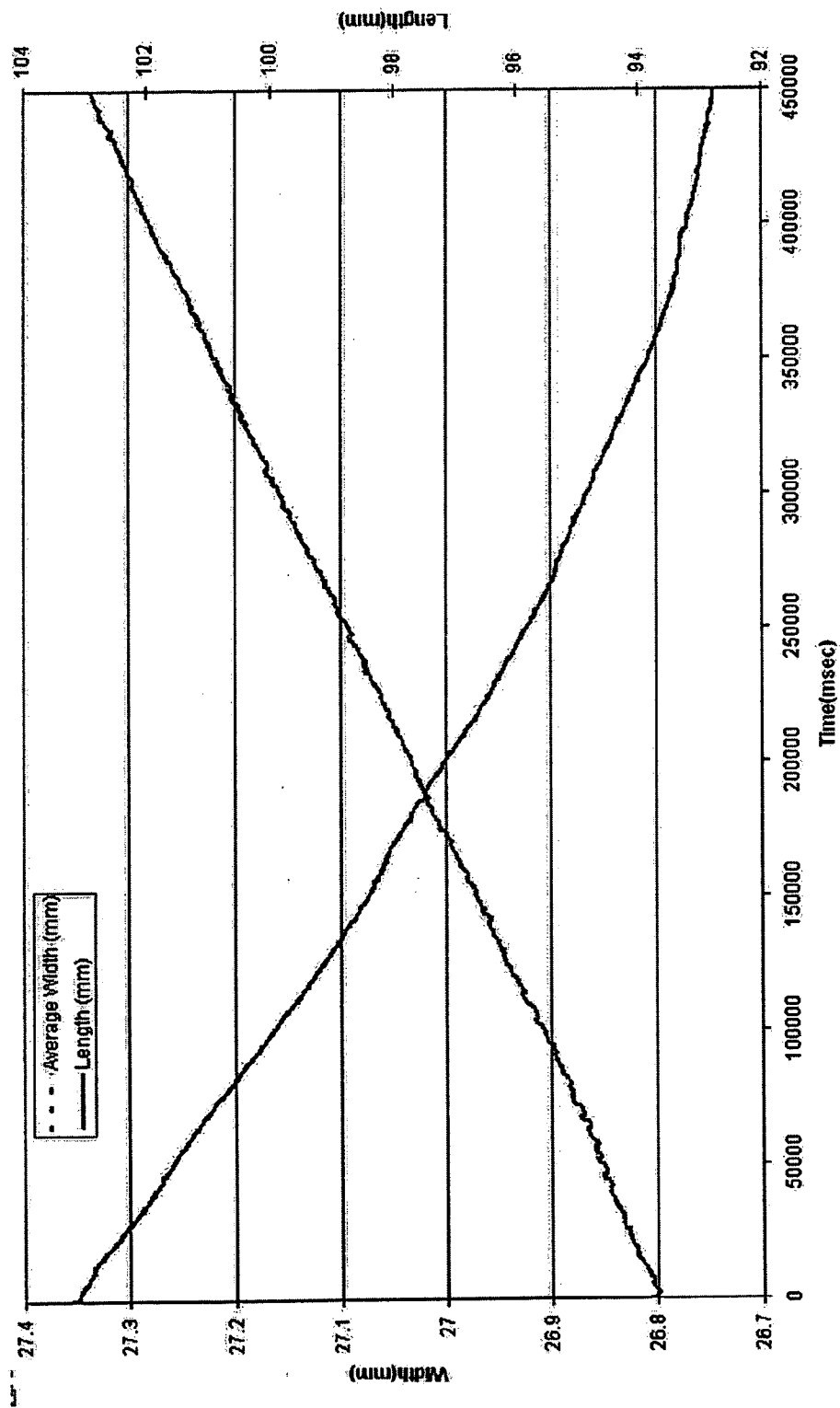


Figure 21a

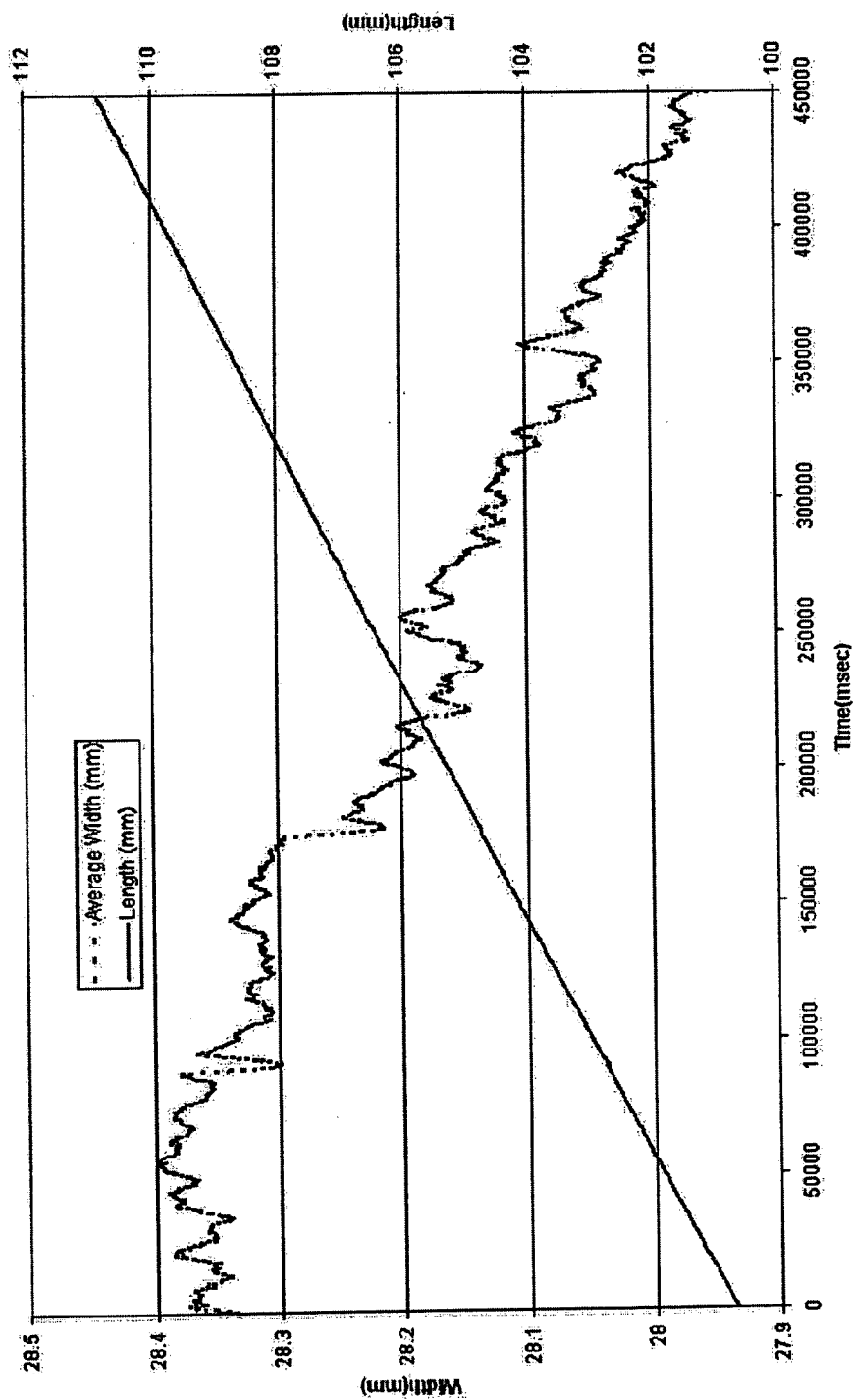


Figure 21b

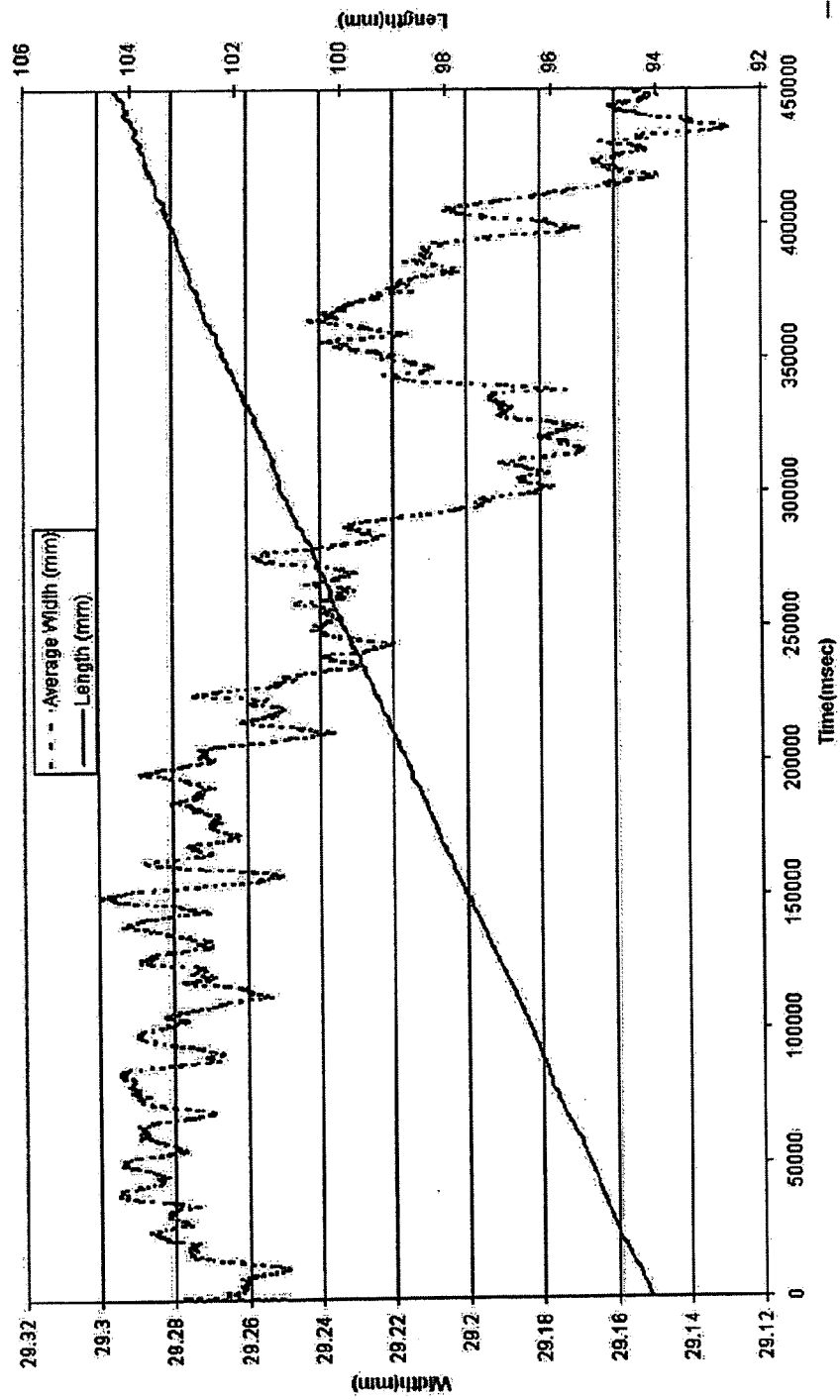


Figure 21c

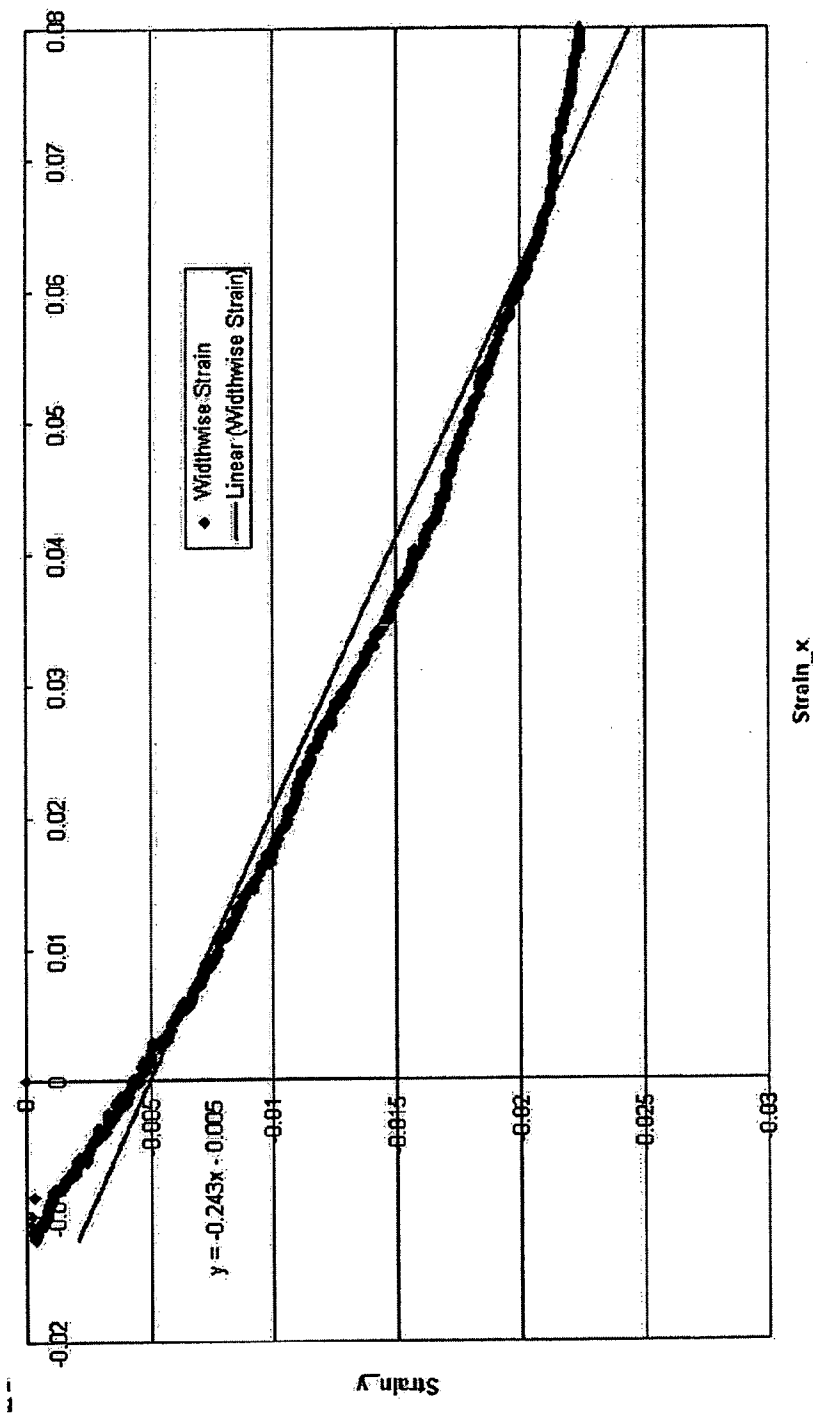


Figure 22a

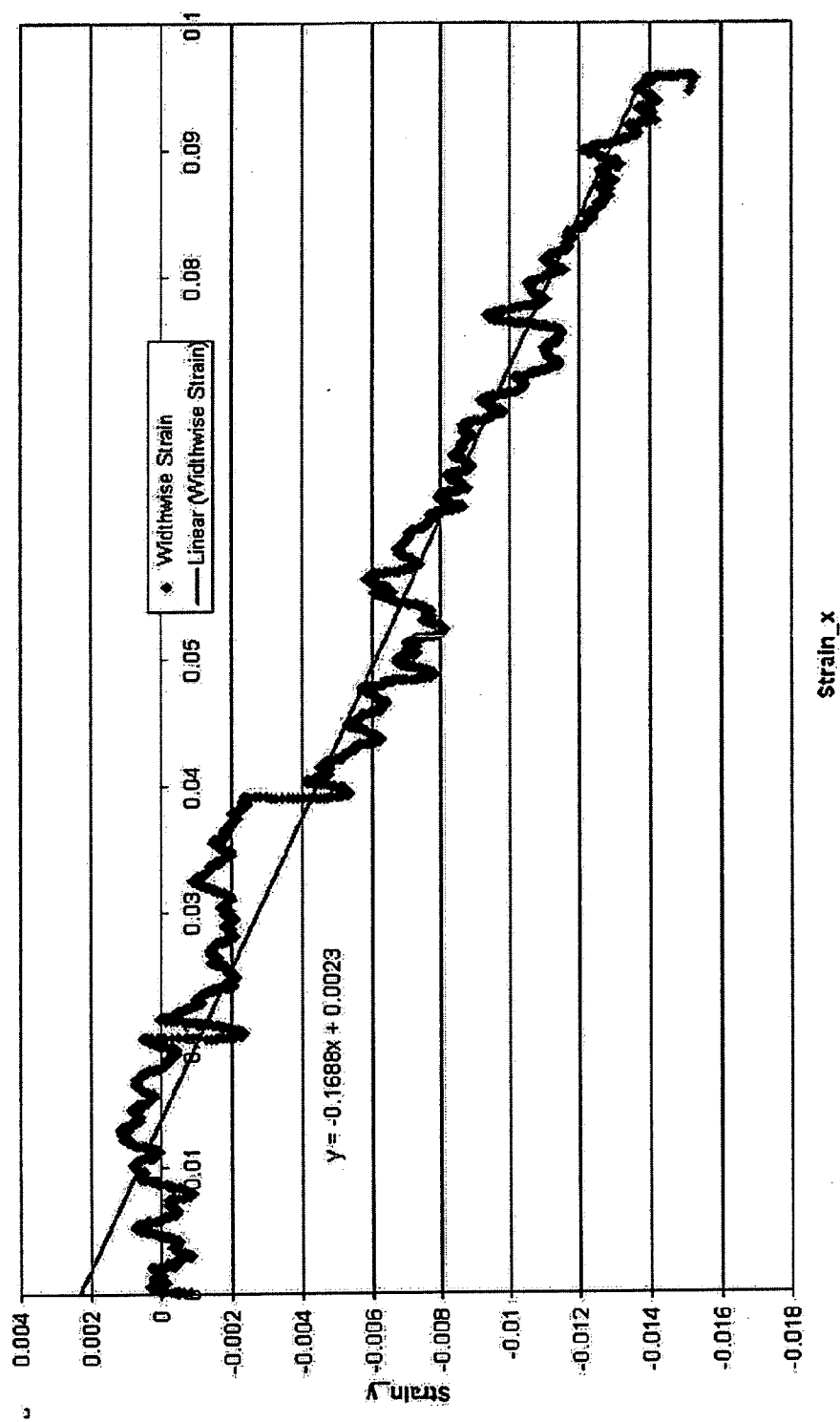


Figure 22b

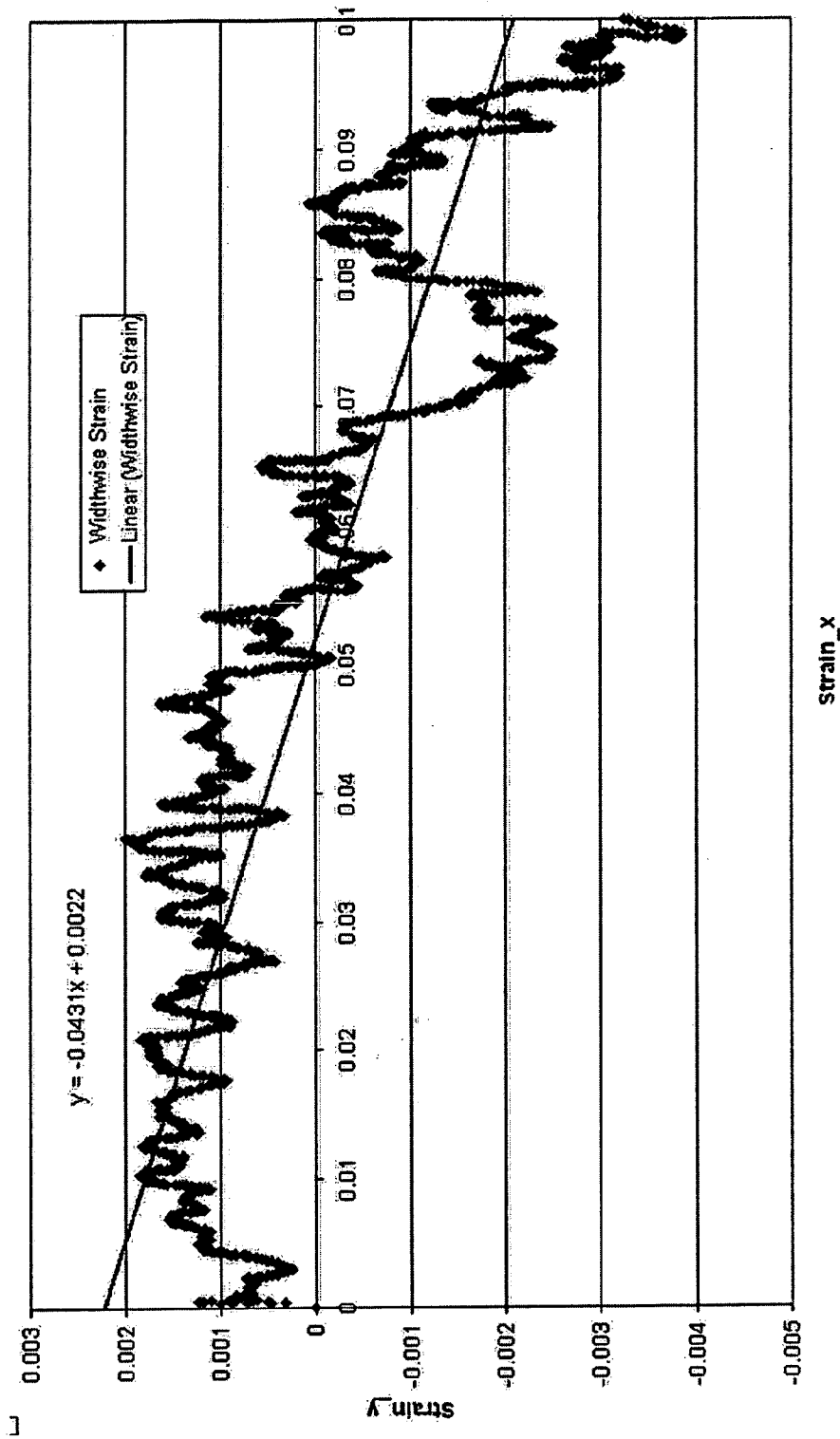


Figure 22c

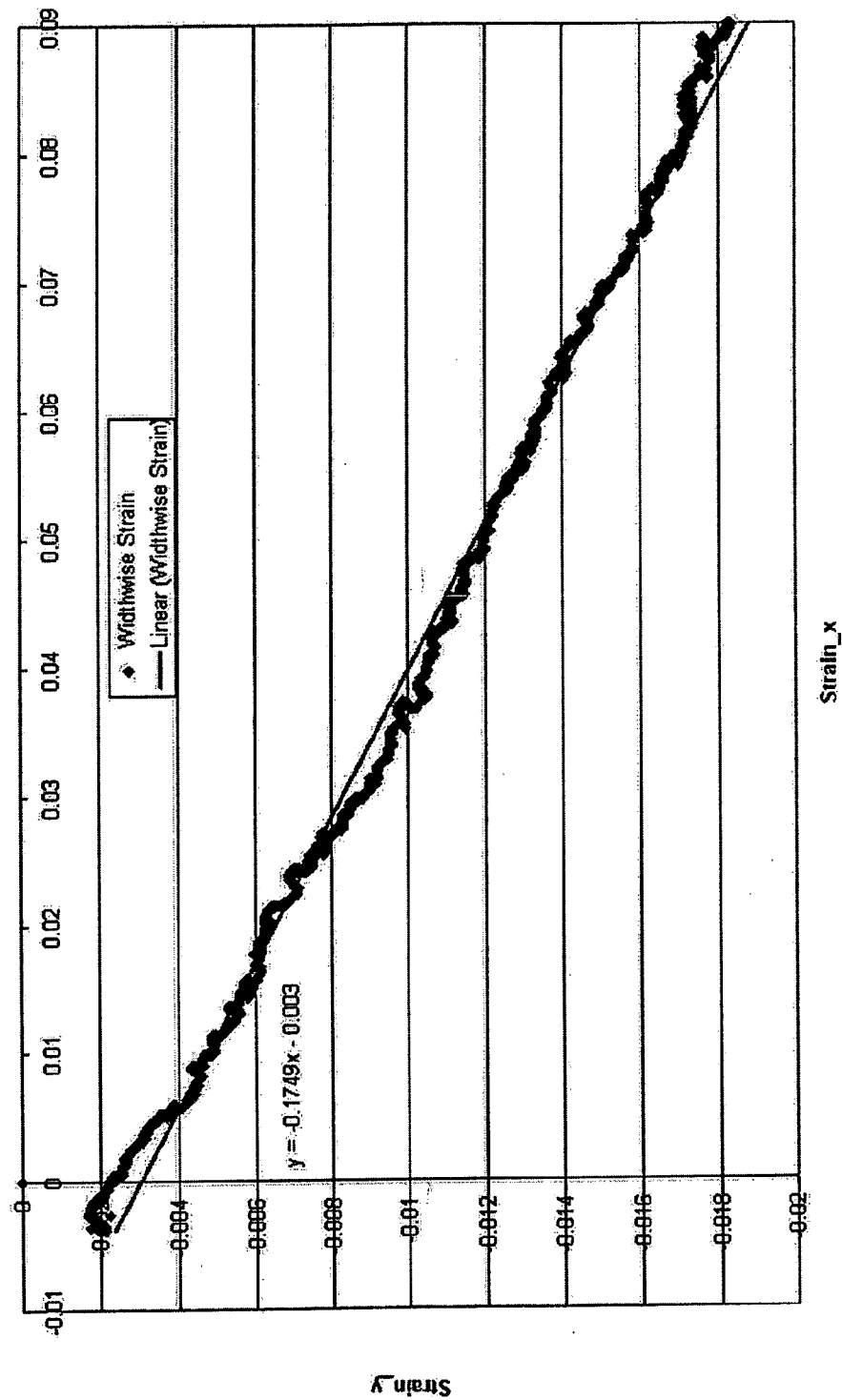


Figure 22d

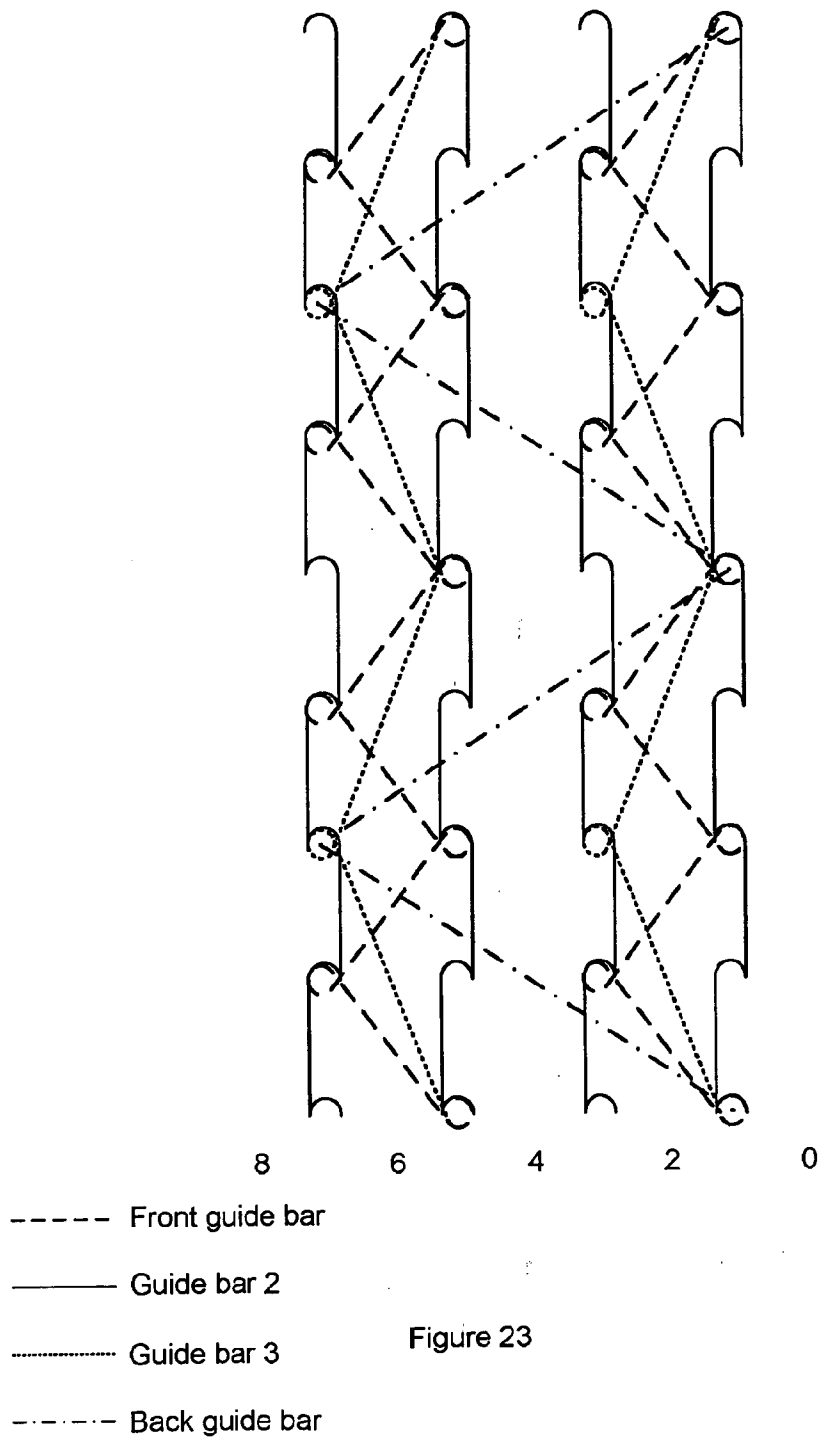


Figure 23

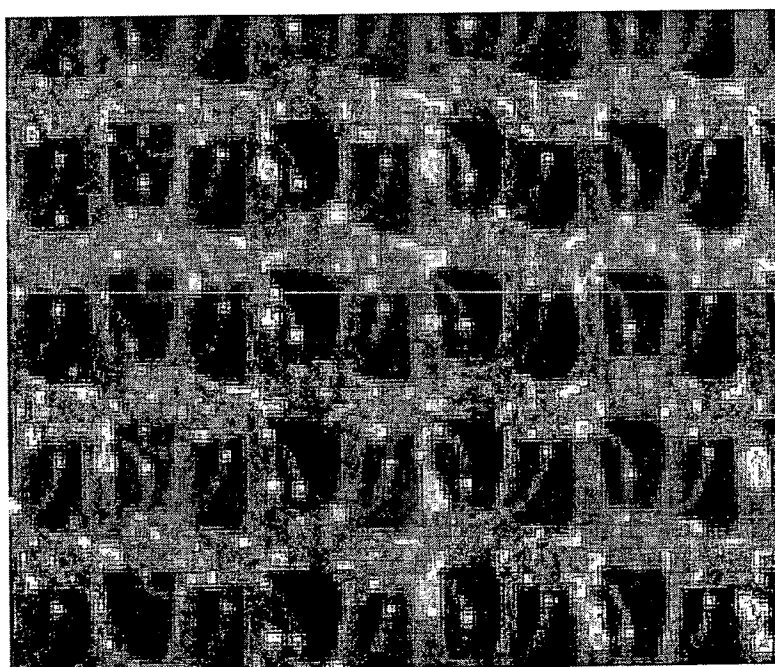


Figure 24

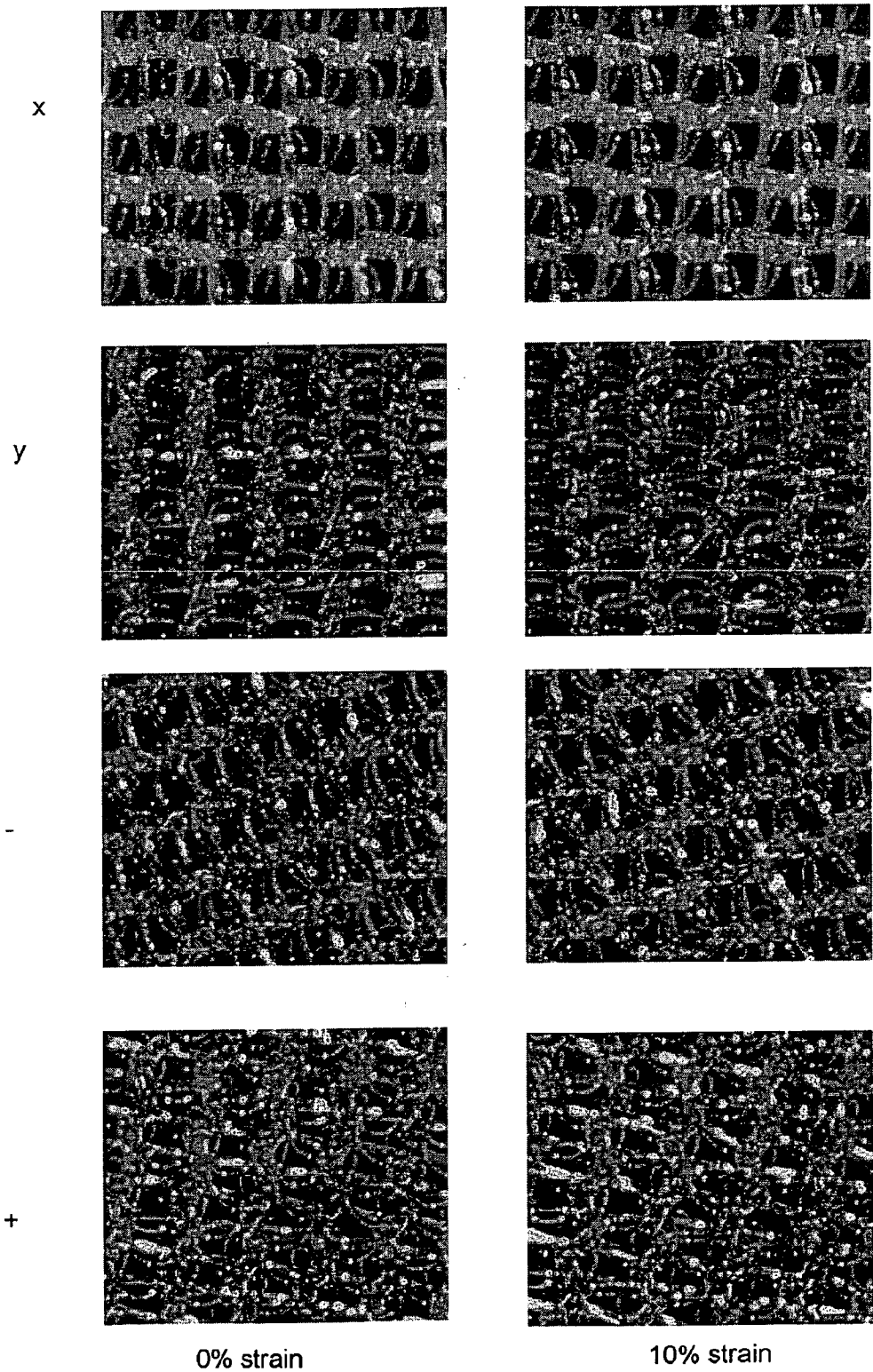


Figure 25

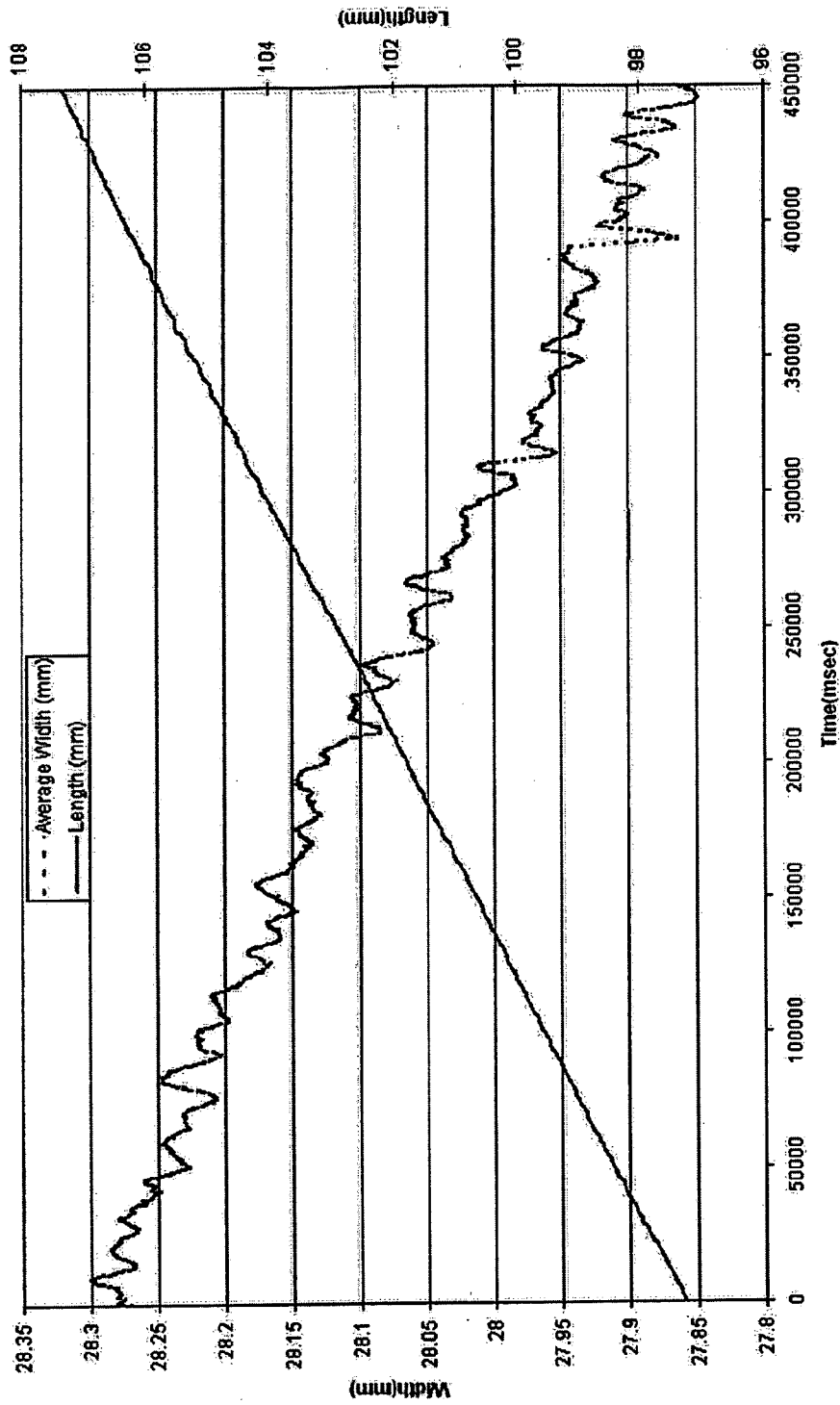


Figure 26a

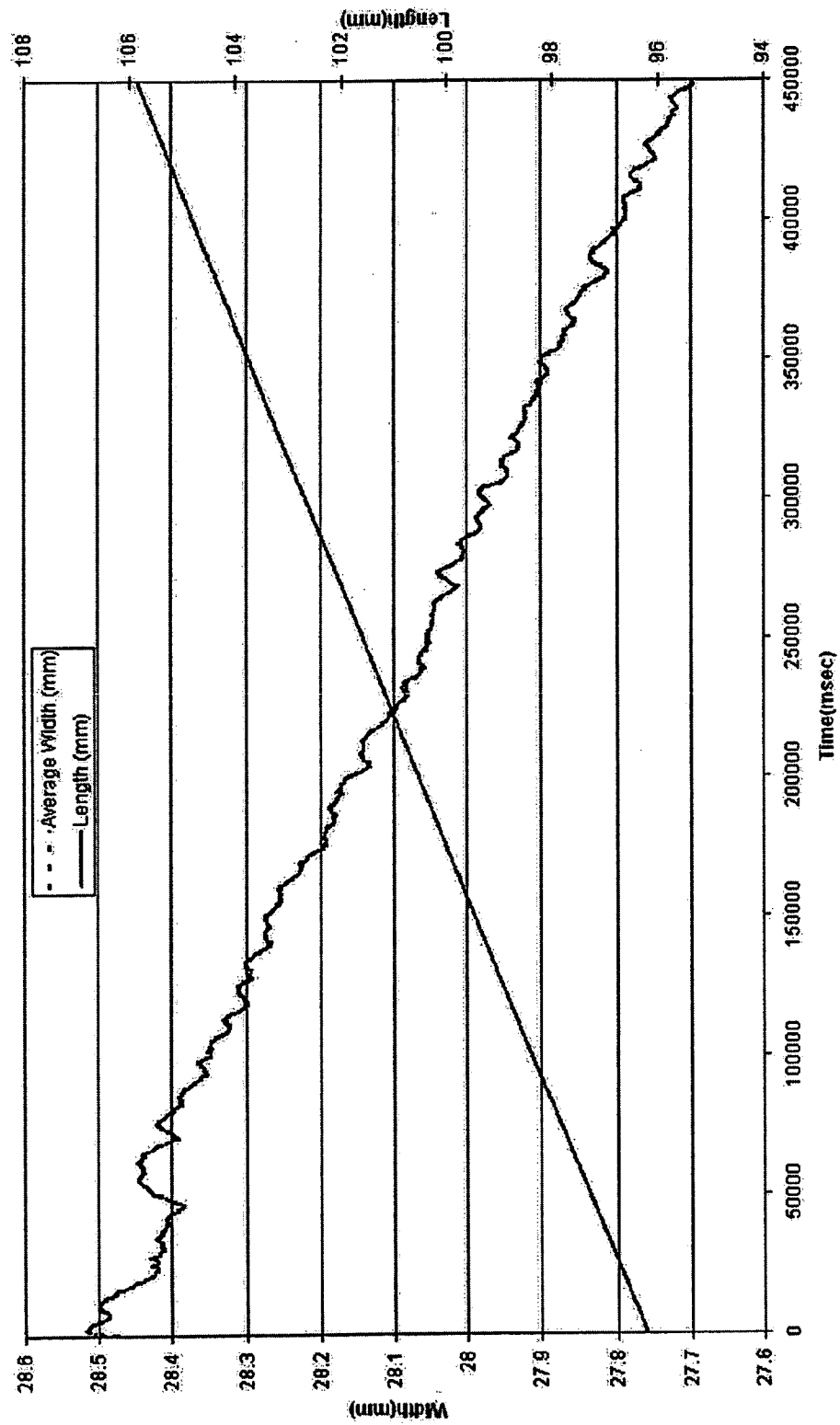


Figure 26b

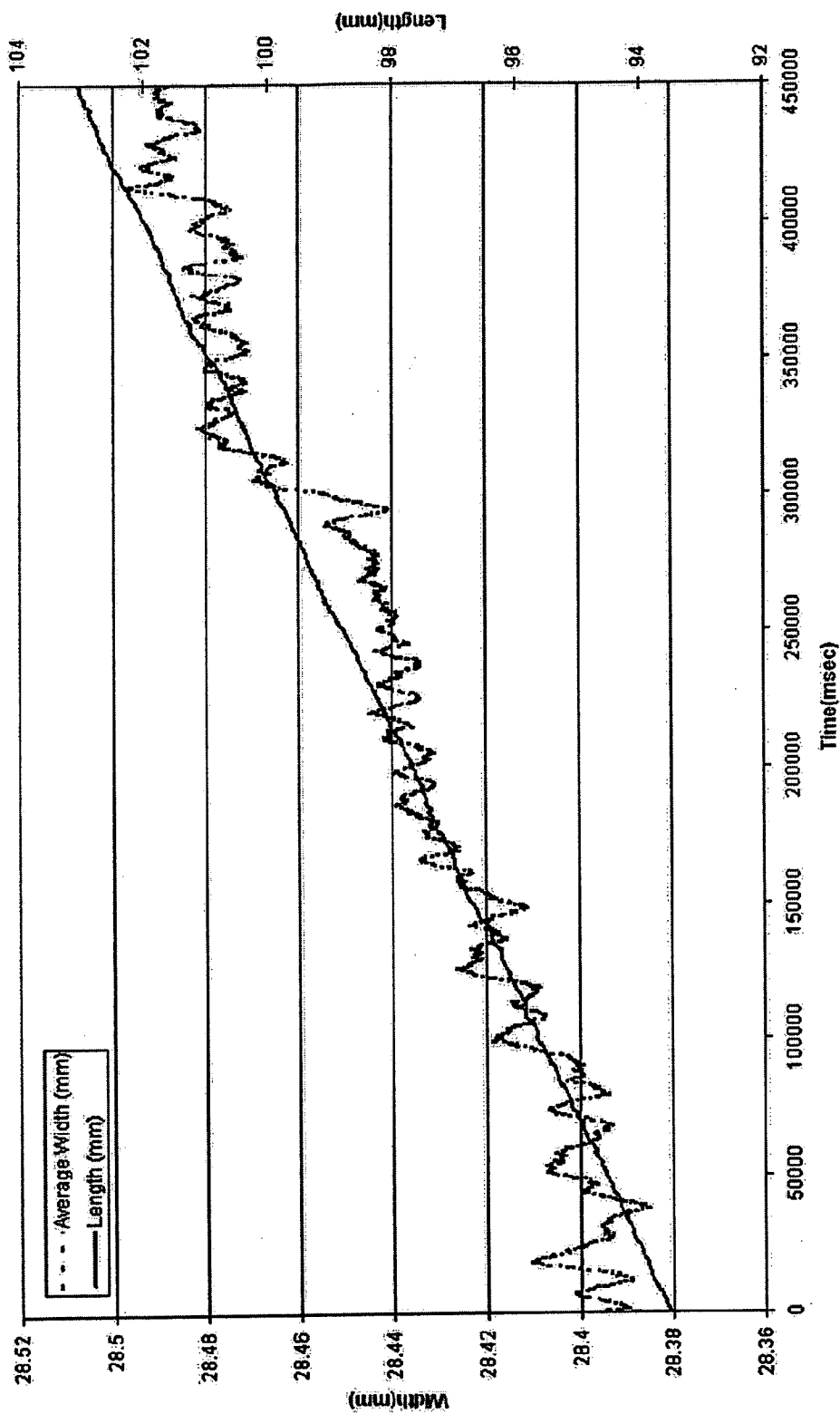


Figure 26c

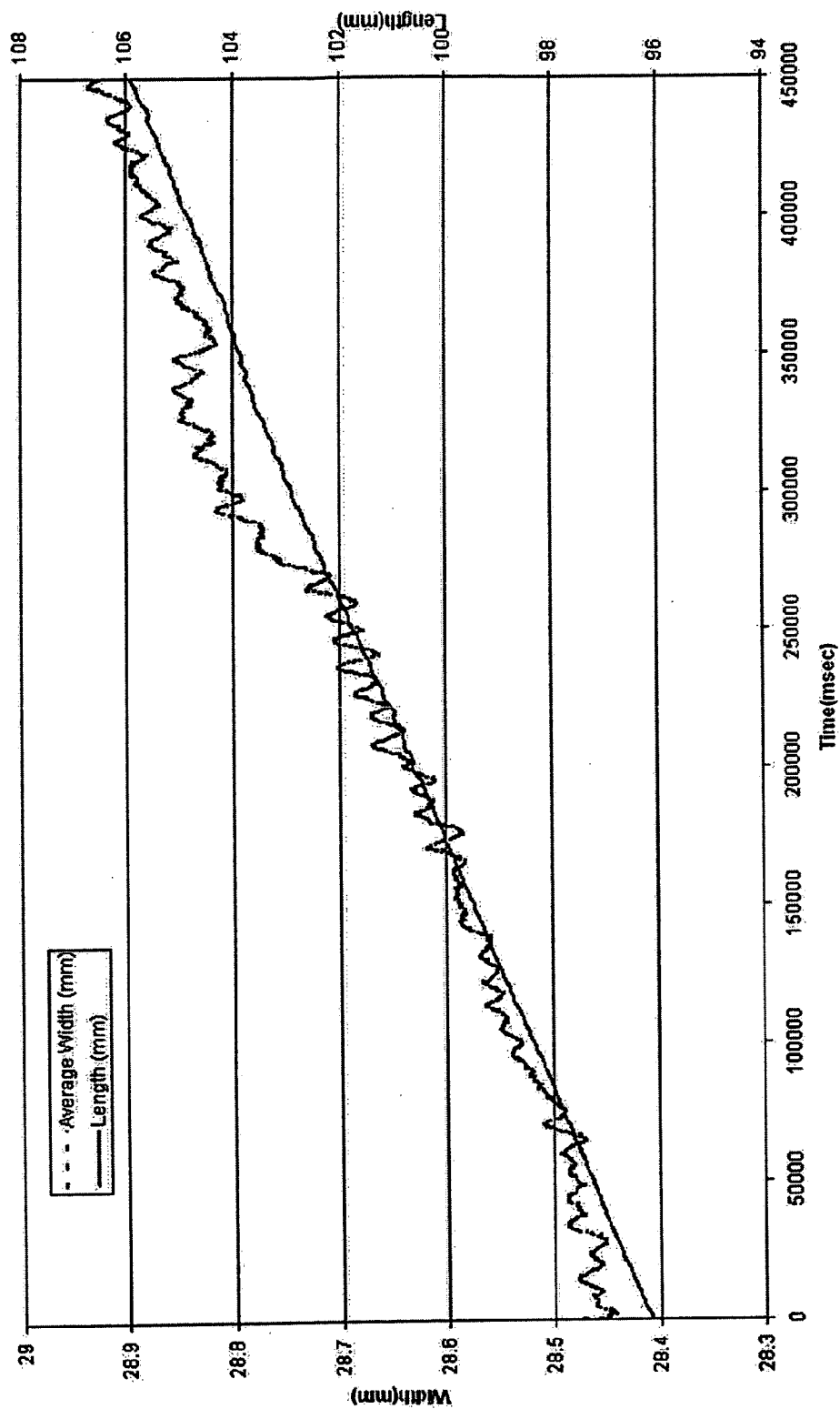


Figure 26d

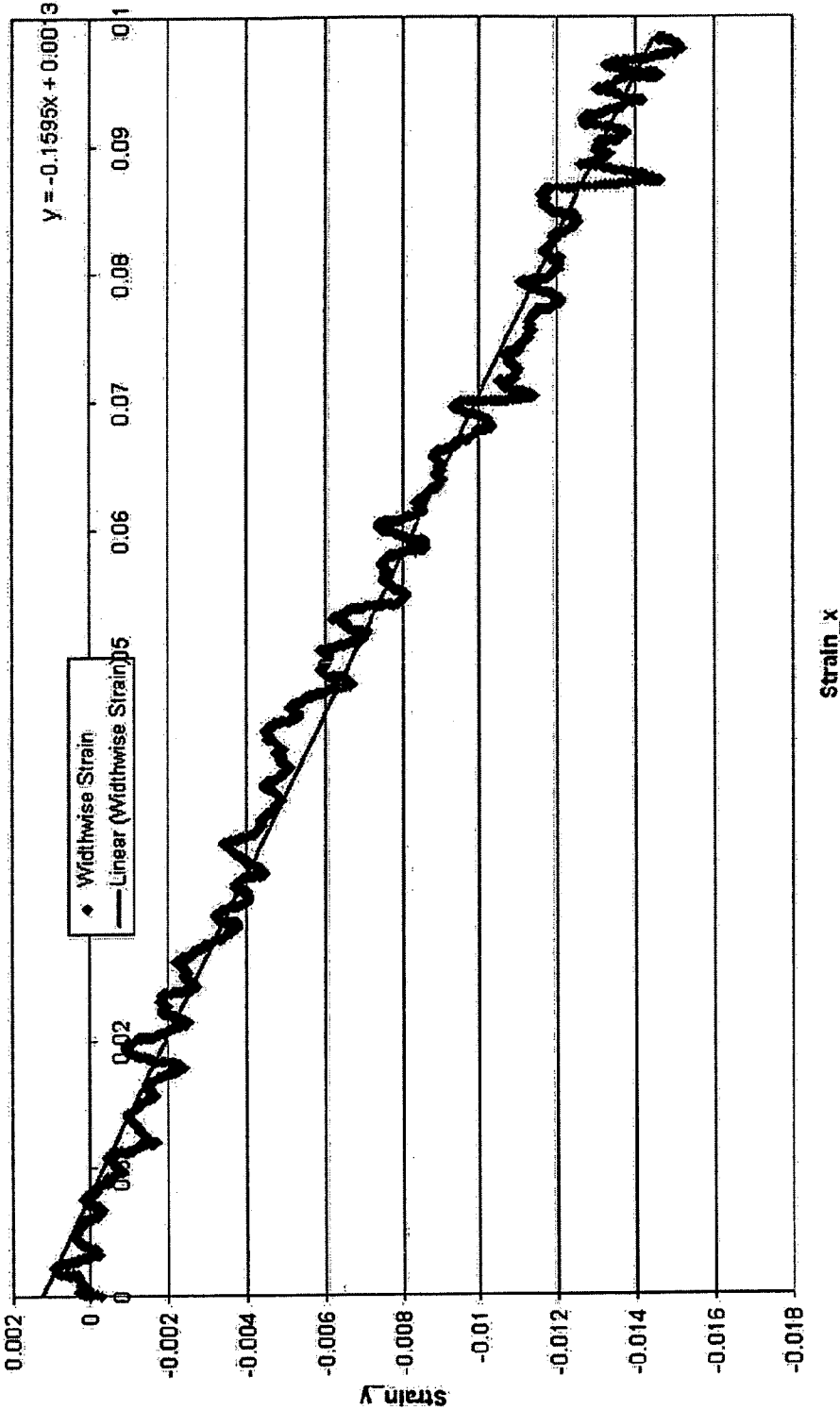


Figure 27a

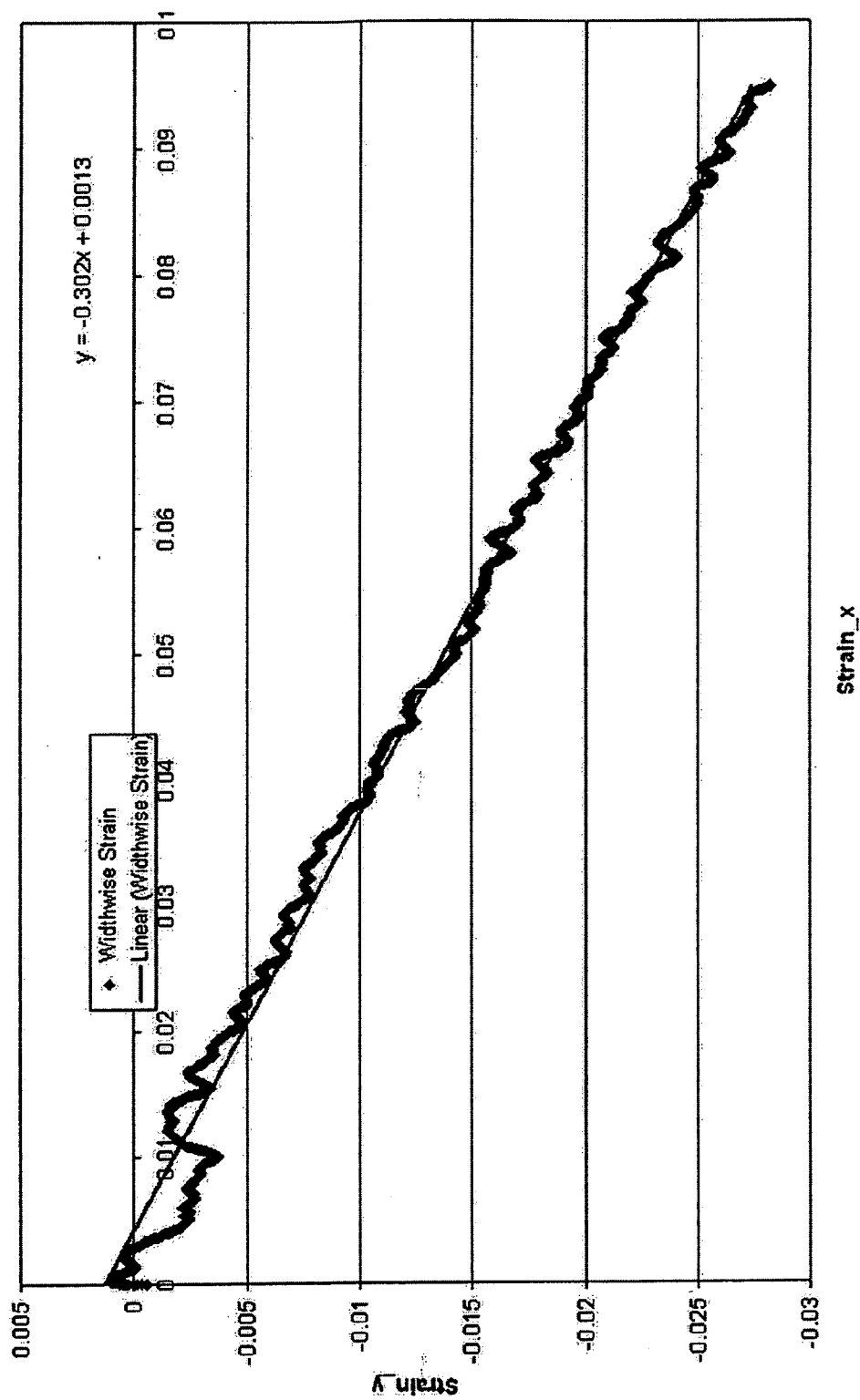


Figure 27b

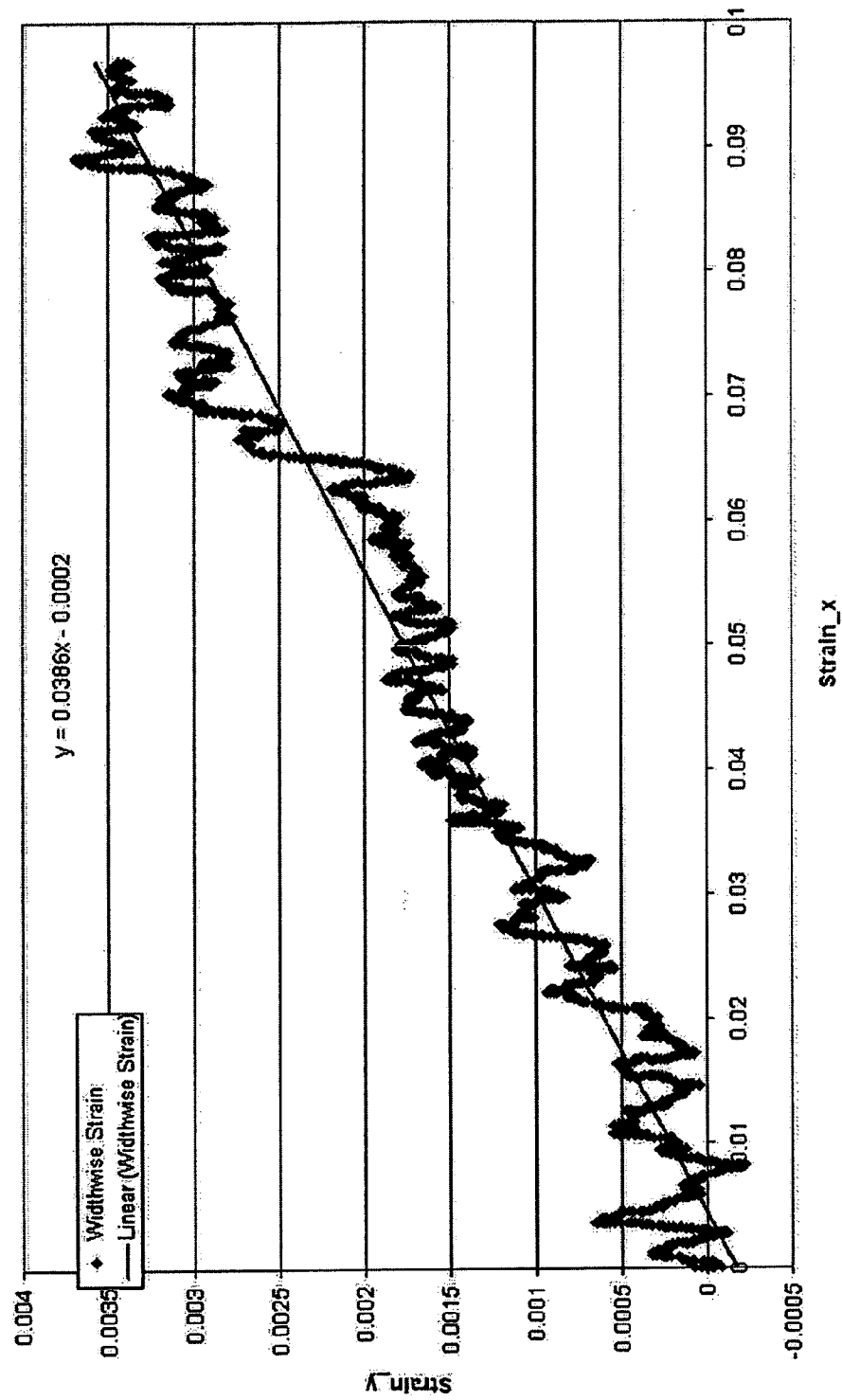


Figure 27c

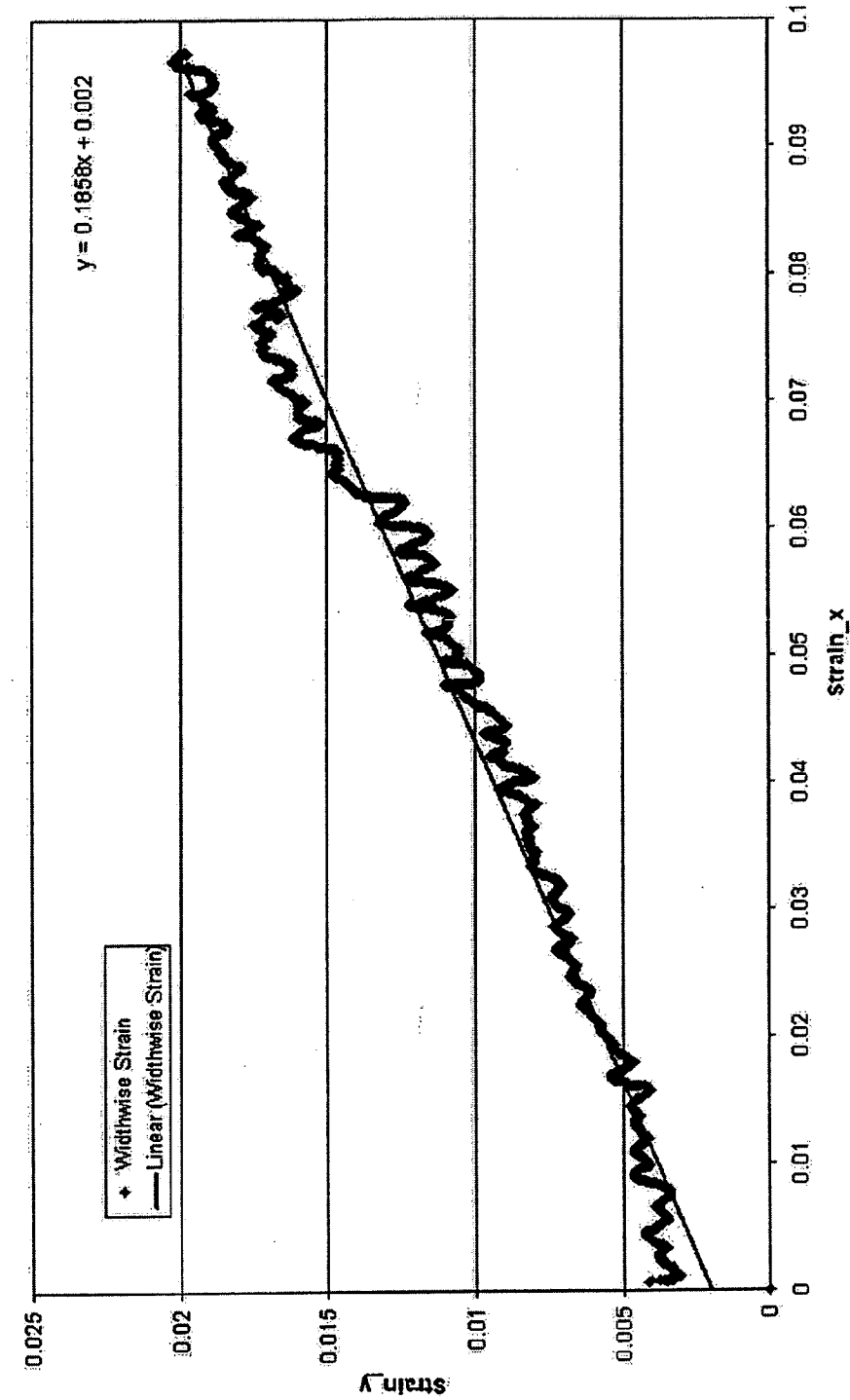
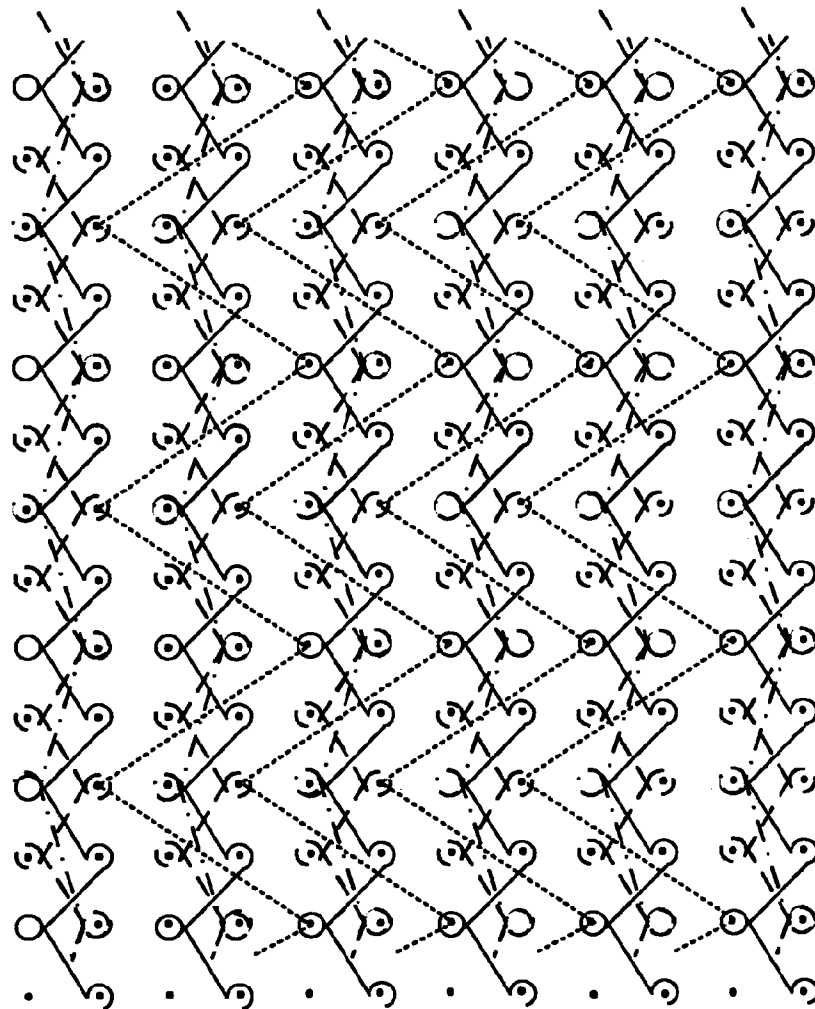


Figure 27d



- Front guide bar
- Guide bar 2
- Guide bar 3
- · - · - Back guide bar

Figure 28

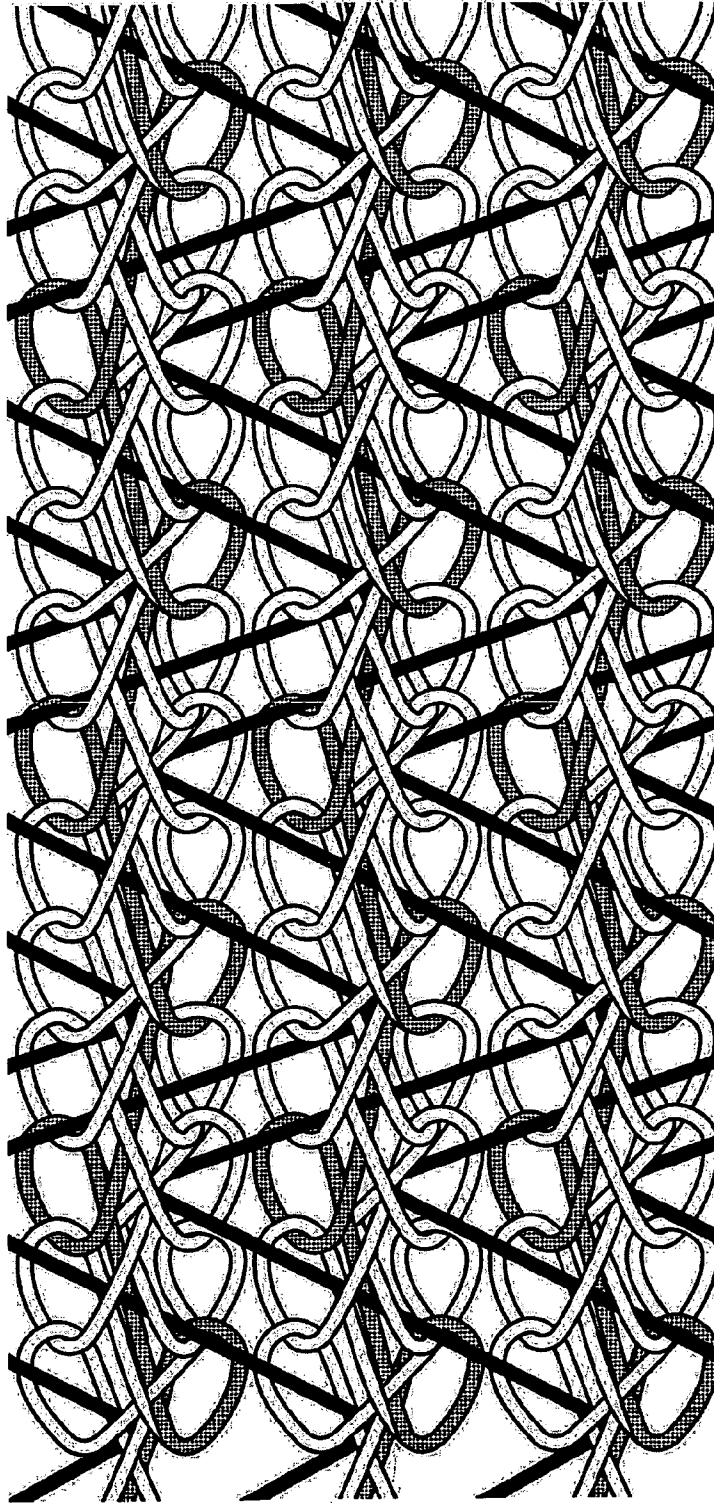


Figure 28a

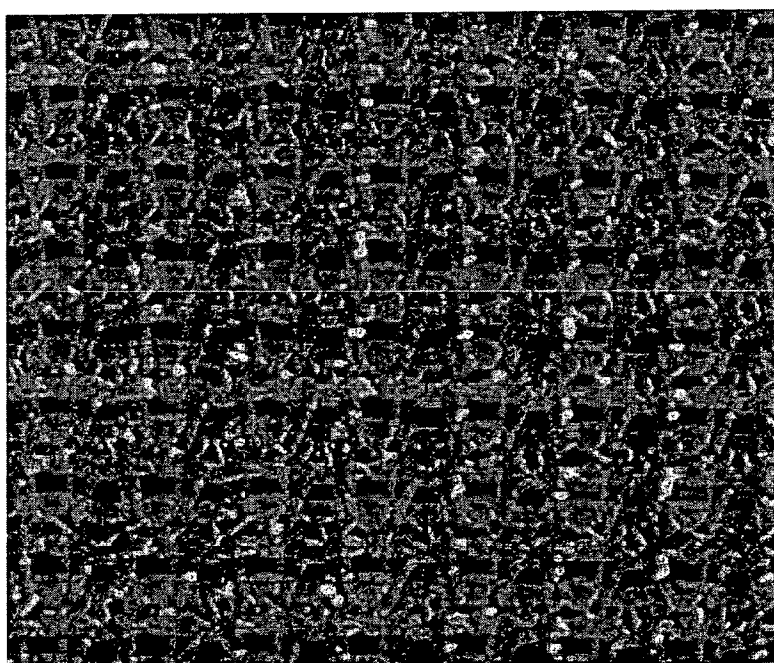


Figure 29

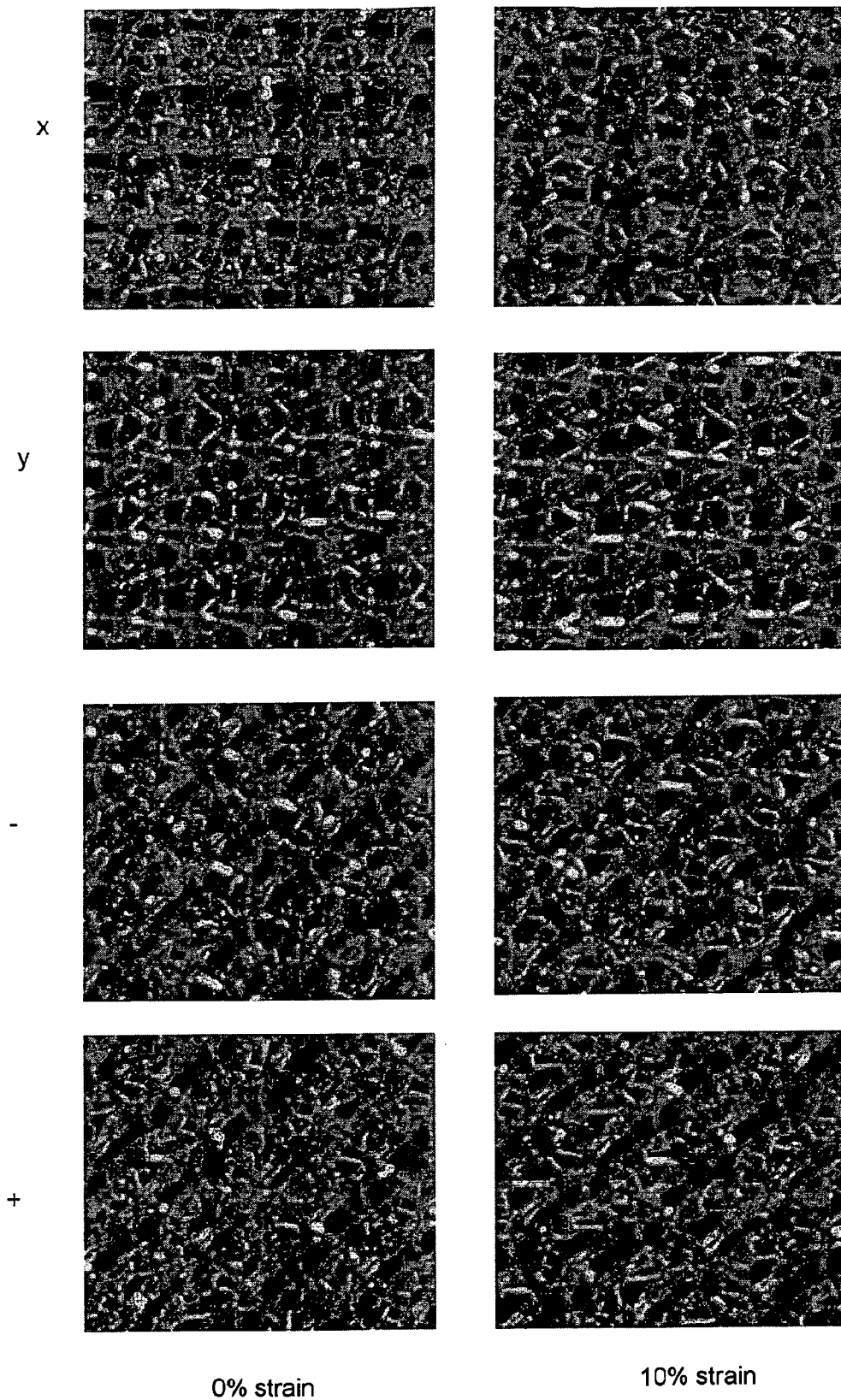


Figure 30

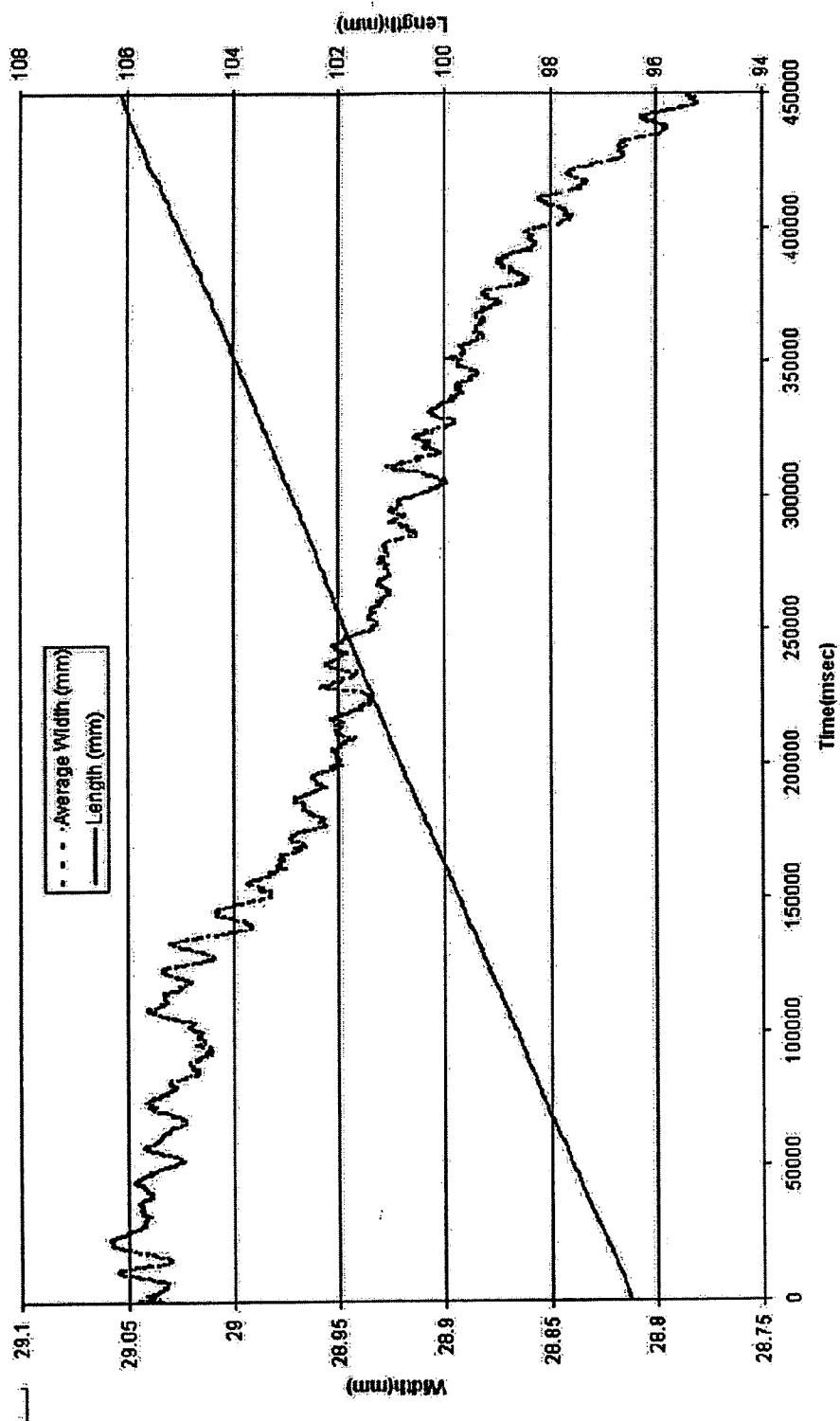


Figure 31a

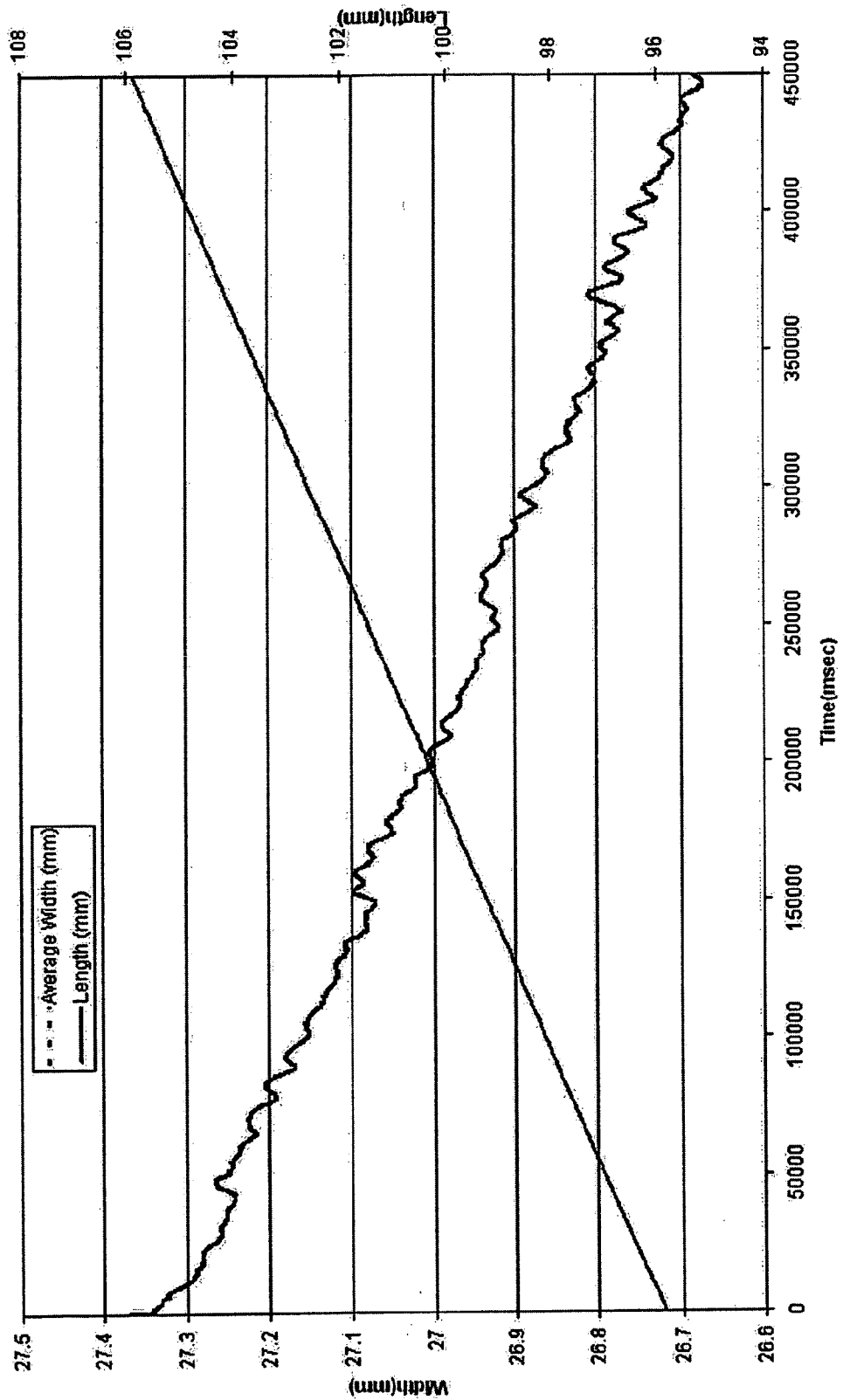


Figure 31b

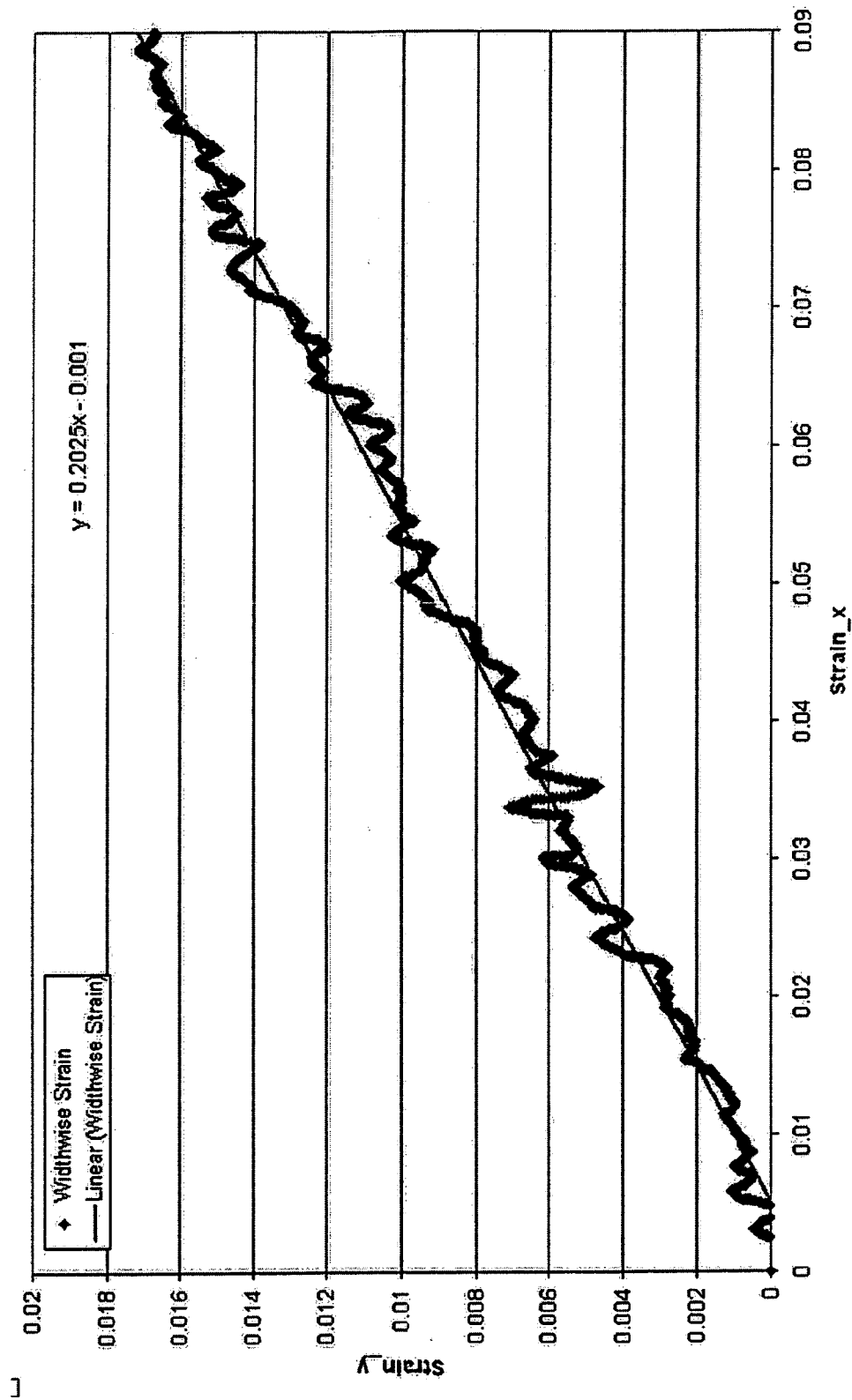


Figure 31c

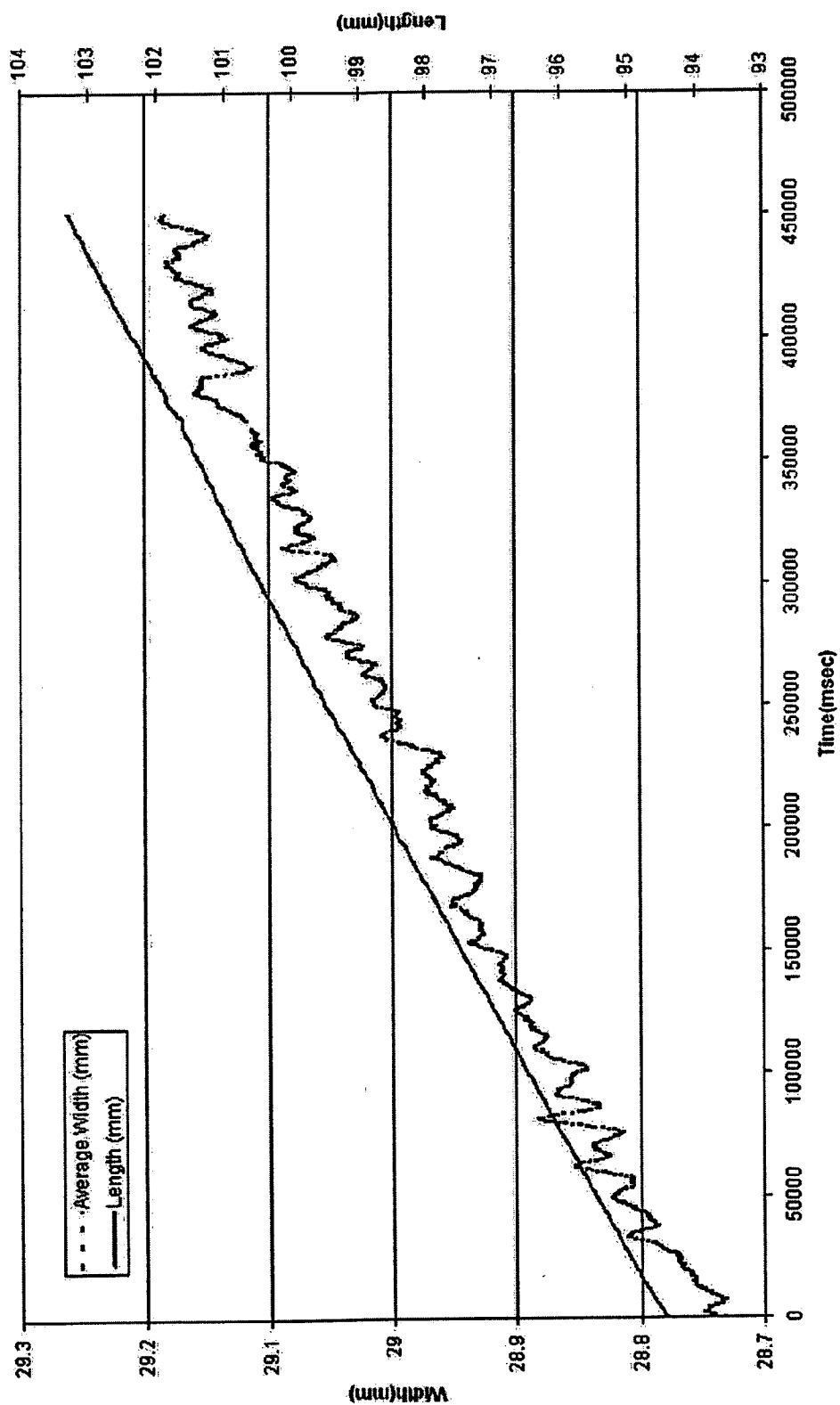


Figure 31d

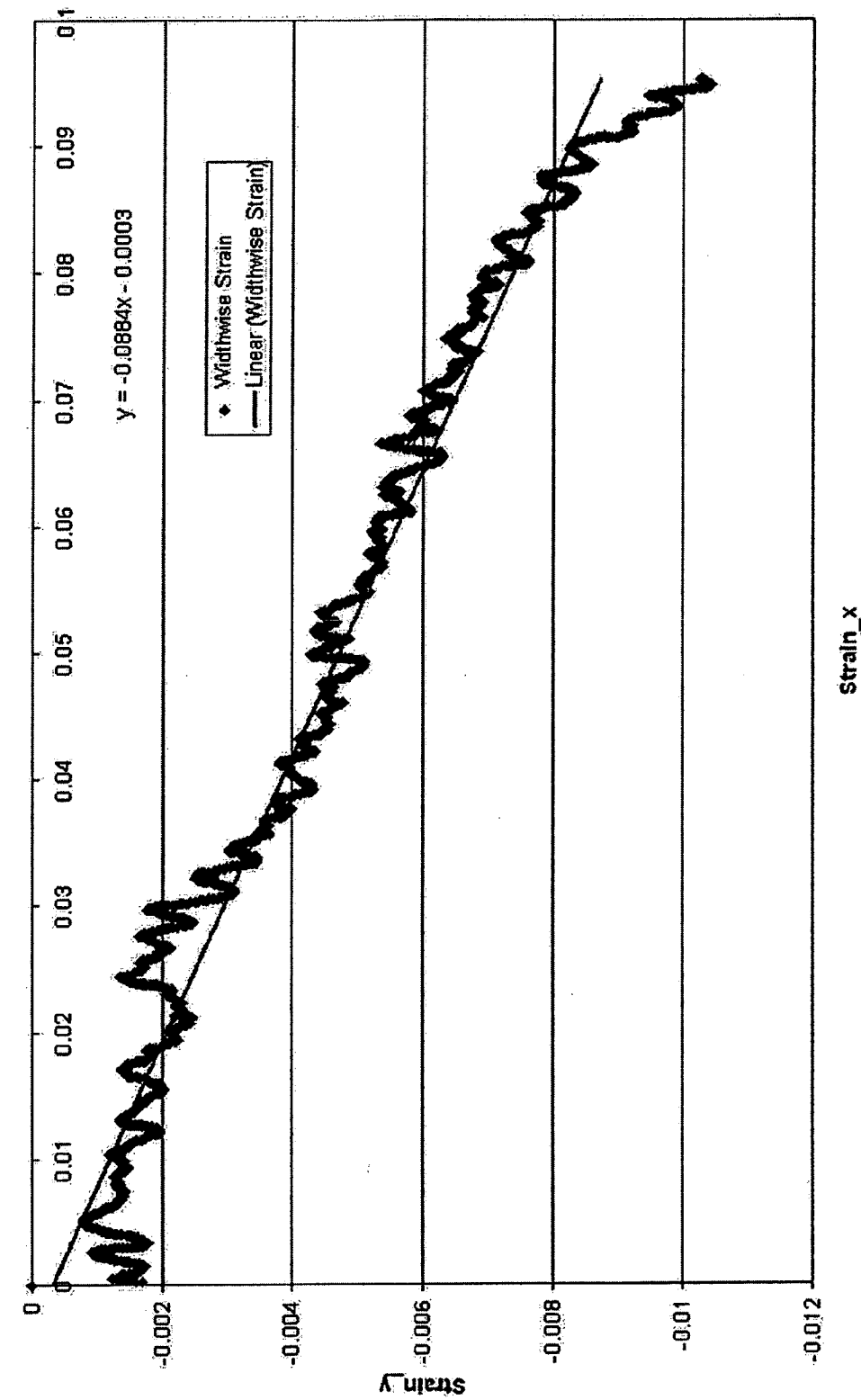


Figure 32a

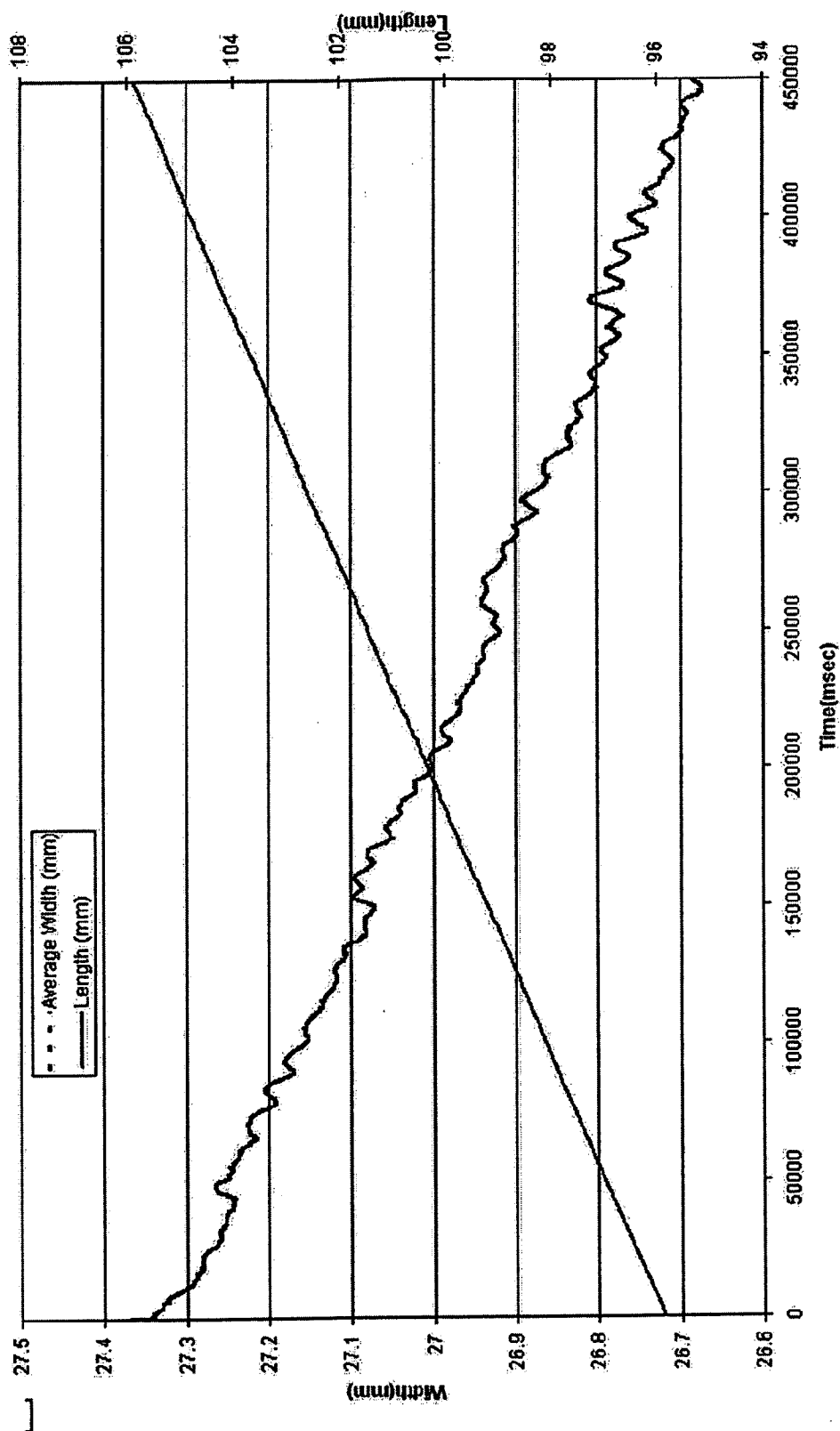


Figure 32b

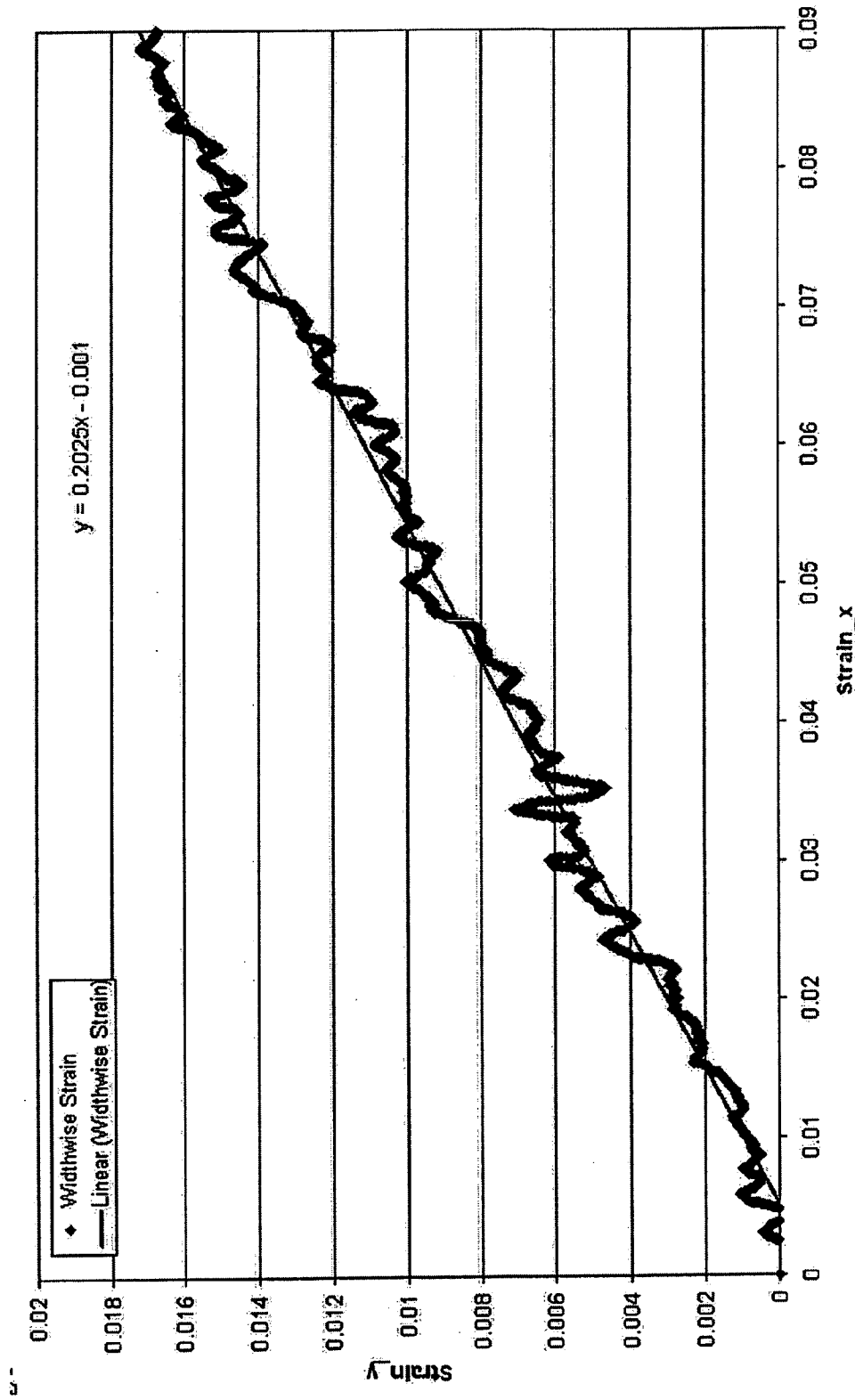


Figure 32c

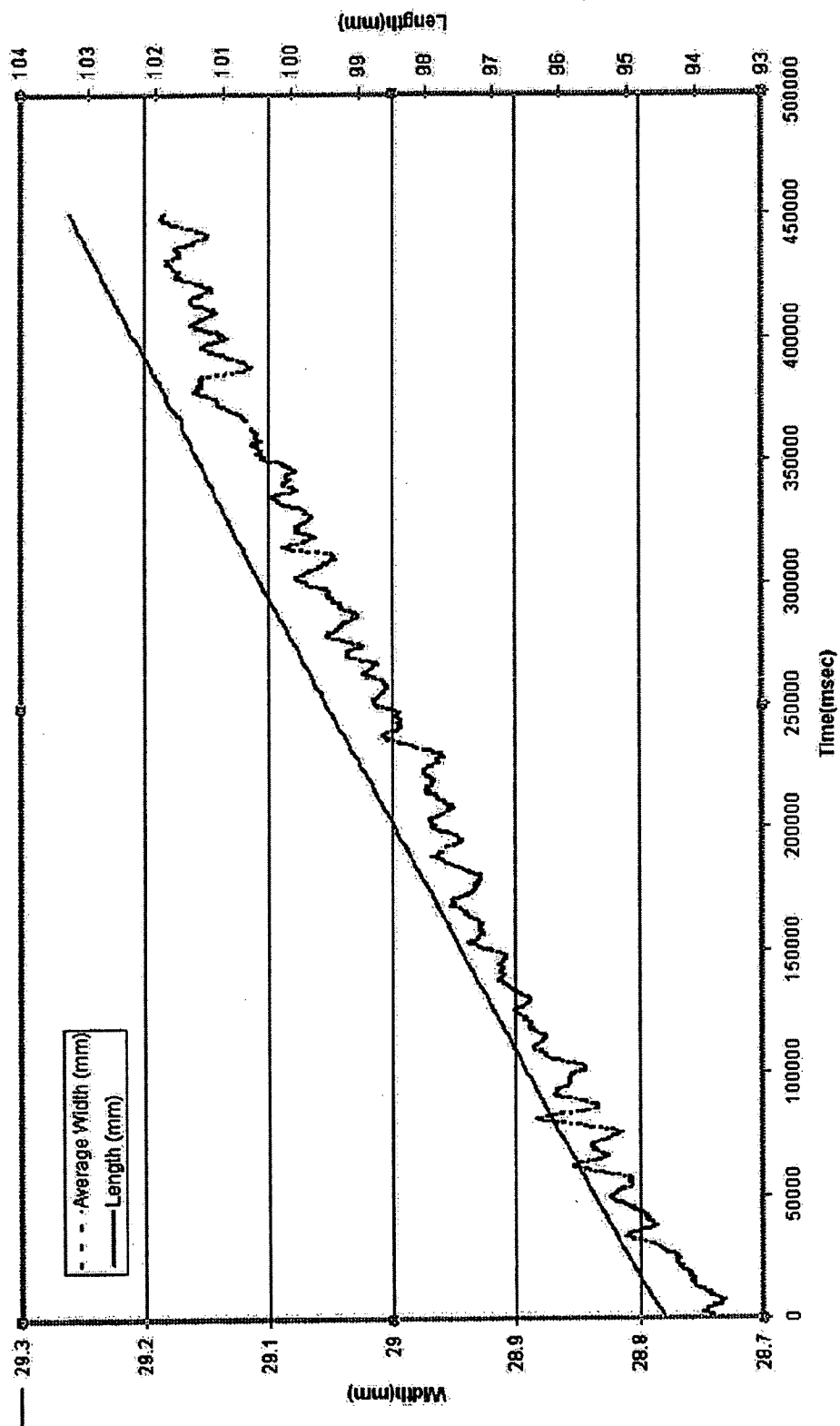


Figure 32d

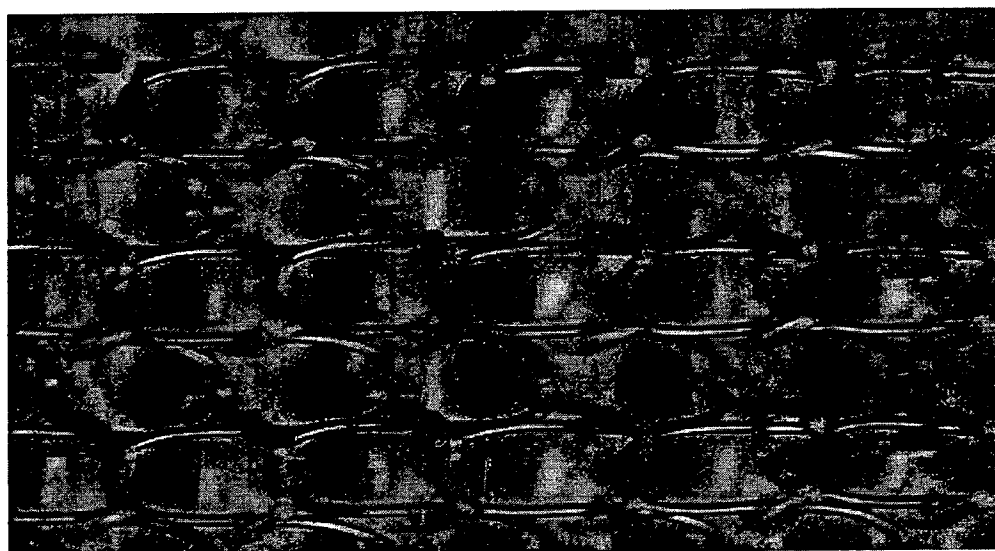
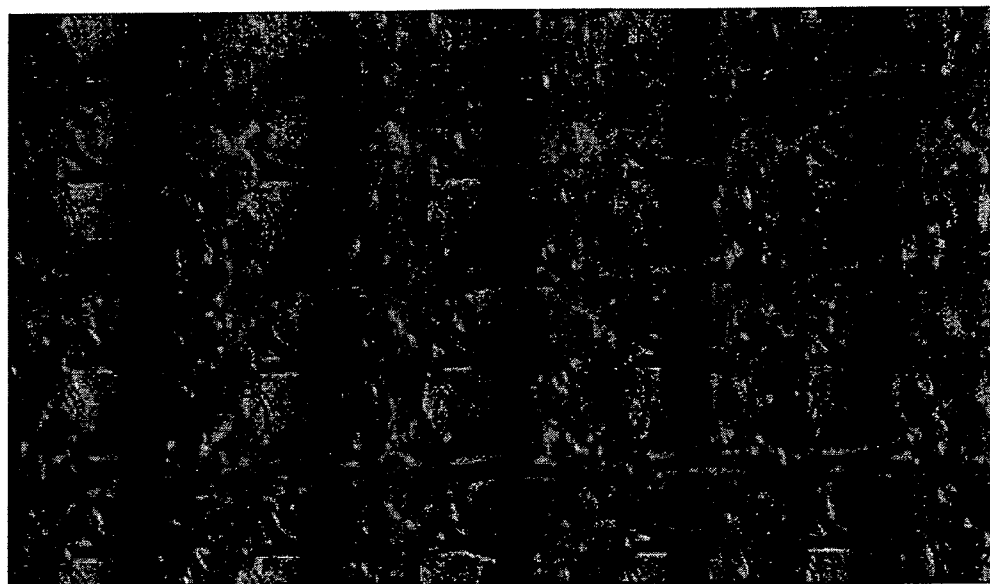
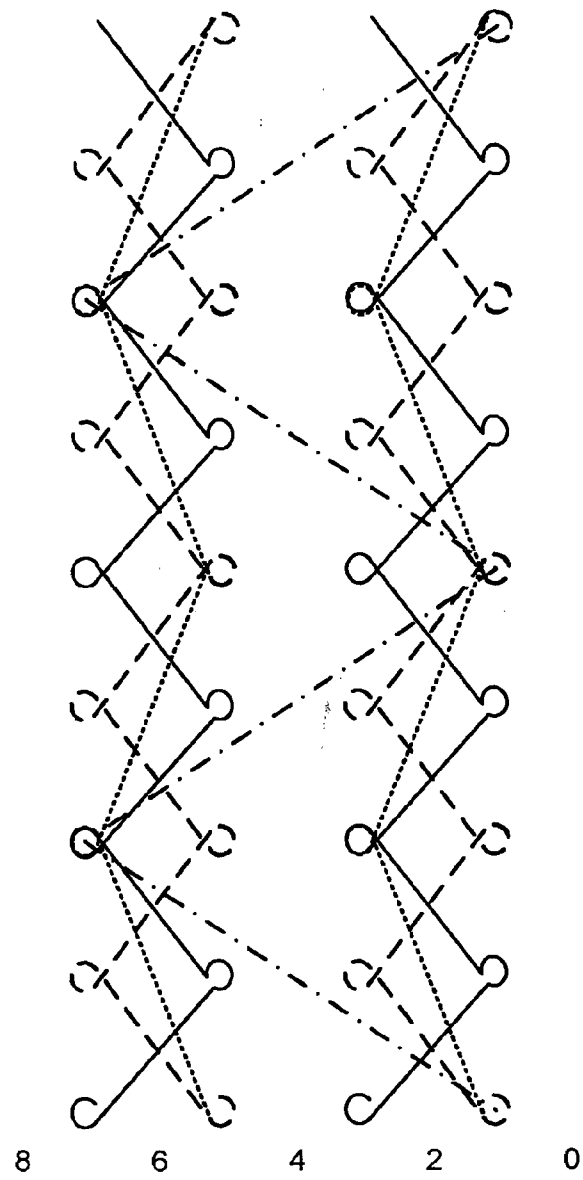


Figure 33



----- Front guide bar

———— Guide bar 2

..... Guide bar 3

- · - · - Back guide bar

Figure 34

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2010/050719

A. CLASSIFICATION OF SUBJECT MATTER

INV. D04B21/18
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

D04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EP0-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2008/016690 A2 (HBI BRANDED APPAREL ENTPR LLC [US]; STARBUCK MICHAEL [GB]; SUBHASH CAN) 7 February 2008 (2008-02-07) paragraphs [0030] - [0041]; claims 1, 5, 7-10; figures 4-9	1,3,4, 7-11
A	US 5 545 470 A (SCHUSTER DIETER H P [DE] ET AL) 13 August 1996 (1996-08-13) column 4, line 3 - column 5, line 8; figure 3; examples 9-11	1,2,5-7

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search

1 September 2010

Date of mailing of the international search report

09/09/2010

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Sterle, Dieter

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2010/050719

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
W0 2008016690 A2	07-02-2008	US 2008011021 A1	17-01-2008
US 5545470 A	13-08-1996	AT 169355 T	15-08-1998
		EP 0675220 A1	04-10-1995