(19) DANMARK

(10) **DK/EP 3147643 T3**

Patent- og Varemærkestyrelsen

(12) Oversættelse af europæisk patentskrift

(51) Int.Cl.: ***G 01 N 3/20 (2006.01)*** ***G 01 N 3/28 (2006.01)***

(45) Oversættelsen bekendtgjort den: **2019-04-29**

(80) Dato for Den Europæiske Patentmyndigheds bekendtgørelse om meddelelse af patentet: **2019-01-16**

(86) Europæisk ansøgning nr.: **15187129.0**

(86) Europæisk indleveringsdag: **2015-09-28**

(87) Den europæiske ansøgnings publiceringsdag: **2017-03-29**

(84) Designerede stater: **AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR**

(73) Patenthaver: **SSAB Technology AB, P.O. Box 70, 101 21 Stockholm, Sverige**

(72) Opfinder: **TROIVE, Lars, SSAB Technology AB, P.O. Box 70, 101 21 Stockholm, Sverige**

(74) Fuldmægtig i Danmark: **Plougmann Vingtoft A/S, Strandvejen 70, 2900 Hellerup, Danmark**

(54) Benævnelse: **FREMGANGSMÅDE OG COMPUTERPROGRAMPRODUKT**

(56) Fremdragne publikationer:
US-A1- 2008 083 288
US-A1- 2008 216 585
T. NAKAMURA ET AL: "analysis of a dynamically loaded three point bend ductile fracture specimen", ENGINEERING FRACTURE MECHANICS, vol. 25, no. 3, 31 December 1986 (1986-12-31), pages 323-339, XP002755749,
J.N FLORANDO ET AL: "a microbeam bending method for studying stress-strain relations for metal thin films on silicon substrates", JOURNAL OF THE MECHANICS AND PHYSICS OF SOLIDS, vol. 53, 31 December 2005 (2005-12-31), pages 619-638, XP002755748,
L. GARDNER ET AL: "experiments on stainless steel hollow section - part 2: member behaviour of columns and beams", JOURNAL OF CONSTRUCTIONAL STEEL RESEARCH, vol. 60, 31 December 2004 (2004-12-31), pages 1319-1332, XP002755732,
CHRISTOS C. CHAMIS: "analysis of the three point bend test for materials with unequal tension and compression properties", NASA TECHNICAL NOTE, vol. D-7572, 1 March 1974 (1974-03-01), pages 1-32, XP002755731,
DE-A1- 19 939 549
FR-A1- 2 915 580

DESCRIPTION

TECHNICAL FIELD

[0001] The present invention concerns a method for characterizing a metallic material, whereby said method may be used to determine the real response of the metallic material during bending. The present invention also concerns a computer program product that comprises a computer program containing computer program code means arranged to cause a computer or a processor to execute the calculating step of a method according to the present invention.

BACKGROUND OF THE INVENTION

[0002] In recent years there has been an increasing interest to utilize ultra-high strength (UHS) steels, i.e. steels with yield strength ≥ 550 MPa or a tensile strength ≥ 780 MPa, in various industries, such as in the automotive, aerospace and construction industries. The use of such material results in considerable improvements in the performance of products comprising such material and a reduction in their weight. However, it is well known that as the strength of a steel increases, its bendability tends to decrease. There is therefore a need to investigate and improve the bendability of high strength steels in order to meet the increasing demands from the market.

[0003] The bendability of metallic materials is usually determined by performing conventional bending tests combined with tensile testing. However, a material's behaviour in a tensile test in which uniform tension is applied though the thickness of a test specimen is different to the behaviour exhibited by that material when it is bent. It has namely been found that tensile test does not provide accurate information concerning a material's bending behaviour, i.e. the real response of a material during bending.

[0004] The Verband der Automobilindustrie (VDA) 238-100:2010 Plate Bending Test for Metallic Materials (hereinafter referred to as the "VDA 238-100 standard") is the standard test procedure that is commonly used to determine the bendability of metallic materials, especially cold-rolled steel. Bending angles are determined using a three point bending device according to the procedure described in the VDA 238-100 standard, which specifies the test conditions, tooling, geometry and experimental settings as well as bendability limit assessment. The VDA 238-100 standard also specifies a method for calculating the bending angle. In order to allow a direct comparison between metals with different thickness, a thickness correction factor equal to the square root of the material's thickness is commonly used.

[0005] During the VDA 238-100 standard bending test, the force required to displace a knife that causes a metal sheet test specimen to bend is monitored. This allows the maximum force and stroke-length achieved during the bending test to be determined. The stroke-length can then be transposed to a corresponding bending angle.. Testing of metallic sheets may be carried out in two directions, namely parallel and perpendicular to a metallic sheet's rolling direction.

[0006] Figure 1 shows typical data obtained using a VDA 238-100 standard test for measuring the knife position or "punch stroke", S (i.e. the distance through which the knife has been displaced) and the applied force, F. According to the VDA 238-100 standard, the knife position at maximum applied force, F_{max}, just before the applied force starts to drop, may be used to determine the bending angle when the test specimen fails.

[0007] Elasto-plastic bending is usually a stable process in which the curvature of a test specimen increases uniformly without kinking. It has been found that the VDA 238-100 standard test does not accurately predict the real response of a metallic material during bending since many metallic materials do not exhibit this perfect elasto-plastic behaviour (i.e. no work-hardening) during bending, and kinking may occur. For example, Z. Marciniak, J.L Duncan and S.J. Hu disclose the following in their book entitled "Mechanics of Sheet Metal Forming", ISBN 0 7506 5300: *"It is very difficult to predict precisely the moment curvature characteristic* [of a metallic material] [i.e. a cross-section moment, M] *from tensile data. The moment characteristic is extremely sensitive to material properties at very small strain and these properties often are not determined accurately in a tension test".*

[0008] Florando et al., Journal of Mechanics and Physics of solids, 53, 2005, pp619-638 discloses a microbeam bending method for studying the stress-strain relations for metal thin films on silicon substrates.

[0009] Three-point bending on hollow members is also known, such as from L. Gardner et al., Journal of Constructional Steel Research, 60, 2004, pp1319-1332.

[0010] T. Nakamura et al., Engineering Fracture Mechanics, Vol 25, No. 3. Pp 323-339, 1986 discloses the use of a three point bending test to investigate fracture mechanics of a ductile specimen.

[0011] The use of a three point bending test to investigate the structural properties of materials having moduli and strengths that are different in tension and compression is disclosed in NASA Technical Note NASA TN D-7572, March 1974, by Christos Chamis. Typically, such materials are structural resins.

[0012] US2008/0216585 discloses a testing device that is capable of applying a constant moment to a material during bending.

SUMMARY OF THE INVENTION

[0013] An object of the invention is to provide a method for characterizing a metallic material, whereby the method may be used to determine a real response of a metallic material during bending, i.e. to more accurately predict the response of a metallic material during bending than predictions based on the data obtained using bending tests (such as the VDA 238-100 standard test) in which the maximum applied force is used to predict the real response of a metallic material during bending.

[0014] This object is achieved by a method of characterising a metallic material that comprises the steps of:

1. a. providing a plate of metallic material simply supported between two parallel rollers, said rollers having the same diameter;
2. b. bending the plate by providing an external force, F, via a bending knife, said force acting in a plane perpendicular to the plane formed by the centres of the rollers and which intersects the plate at the centre line between the rollers, said bending knife extending at least the entire length of plate;
3. c. the method **characterised by** comprising the step of calculating a cross-section moment, M, of the metallic material using the following equation:

$$M = \frac{F \cdot L_m(\beta_1)}{2 \cdot cos^2(\beta_1)}$$

where F is the applied bending force,

$L_m(\beta_1)$ is the moment arm, calculated according to the following equation:

$$L_m(\beta_1) = L_0 - (R_k + R_d) \cdot \sin(\beta_1)$$

where

L_0 is half the die width,

R_d is the radius of the die edge,

R_k is the radius of the knife, and

β_1 is the bending angle.

[0015] The bending angle, β_1, is the angle moved by the surface normal of the plate at the contact point with one of the rollers during bending by the external force (i.e. 90° (or π/2 radians) minus the acute angle between the normal vectors of the start and bent planes of the plate, the start plane corresponding to the plane formed by the centre lines of the two parallel rollers, and the bent plane corresponding to the plane formed by the centre line of one roller and the line of contact between that roller and the plate, which plane contains the normal of the plate at the point which contacts the roller).

[0016] For a plate which is initially horizontal, this is equivalent to the angle between the surface normal of the plate at the contact point with one of the rollers and the vertical. In a preferred embodiment, this object is achieved by a method that comprises the steps of carrying out a bending test according to the VDA 238-100 standard or a similar friction-free bending test , i.e. by carrying out a plate bending test as described in said standard using the test equipment described in said standard, preparing the samples in the way described in said standard, under the test conditions described in said standard, using the procedure described in said standard and determining a bending angle, β_1 (equal to half the bending angle α from the VDA 238-100 standard), from the punch stroke as described in the standard. The method also comprises the step of calculating a cross-section moment, M, of the metallic material using the following equation:

$$M = \frac{F \cdot L_m(\beta_1)}{2 \cdot cos^2(\beta_1)}$$

where F is the applied bending force,

L_m (β_1) is the moment arm, and

β_1 is the bending angle.

[0017] This calculated cross-section moment, M, may then be used to predict the real response of the metallic material.

[0018] By calculating the cross-section moment of the metallic material (rather than the applied force that is usually determined using tests such as the VDA 238-100 standard test), the flow stress, σ_1 (i.e. the approximate cross-section stress-profile profile in the bent metallic material), may consequently be determined, using the following equation:

$$\sigma_1 = \frac{2}{B \cdot t^2 \cdot \varepsilon_1} \cdot \frac{d}{d\varepsilon_1}(M \cdot \varepsilon_1{}^2)$$

where the main strain, ε_1 is calculated from:

$$\varepsilon_1 = \beta_2 \cdot \frac{t}{L_m(\beta_1)}$$

where B is the length of bend (i.e. the length of the plate in the dimension running parallel to the die supports), t is the sample thickness in mm, (see Figures 3a and 3b). β_2 is the true angle (in degrees) to which said metallic material is bent.

[0019] As used herein, the width, ***L***, of the plate is the dimension that runs across the die opening (i.e. between the pair of parallel die supports), the length, ***B***, of the plate is the dimension that runs parallel to the die supports, while the thickness, t, of the plate is the dimension that runs in the direction travelled by the knife during bending. Thus, by "bending knife extending at least the entire length of the plate" is meant that the bending knife is capable of exerting the force across the entire plate, such that an even bend is formed without any buckling.

[0020] By "die supports" is meant the edges of the die that are in contact with the metallic plate. In the present invention, the die supports are the outer edges of the roller (i.e. cylinders that rotate freely around an axis). The two die supports are parallel to ensure an even distance across the die opening.

[0021] The method according to the present invention allows all parts of a metallic material's response to bending to be determined throughout its entire thickness from its outer surface to its centre using just one simple bending test (rather than when using e.g. the VDA 238-100 standard test and determining only the maximum applied force).

[0022] The method according to the present invention may also be used to indicate when a metallic material exhibits plastic strain localizations. Kinking may also be predicted using the method according to the present invention.

[0023] The present invention is based on the insight that standard tests such as the VDA 238-100 standard do not accurately predict the real response of a metallic material to bending. Experiments carried out by the inventor using the VDA 238-100 standard test have included cases in which no failure of metallic materials has occurred even when the maximum bending force as determined by the VDA 238-100 standard test has been exceeded. The inventor has found that the applied bending force in the VDA 238-100 standard test always reaches a maximum level and then decreases, due to a decreasing angular speed in bending (this can be demonstrated theoretically). Determination of the cross-section moment, M, (and not the applied bending force) therefore provides a more accurate prediction of the real response of a metallic material to bending.

[0024] Additionally, using the methodology of the invention, the angular position when the natural force-maximum occurs can be determined by minimizing the invented force formula.

$$\frac{dF}{d\beta_1} = 0$$

[0025] Thus, assuming a constant moment, M, when the cross-section is fully plastified, then ;

$$\beta_{F\,max} = \sin^{-1}\left[\frac{L_0 - \sqrt{{L_0}^2 - (R_d + R_k)^2}}{(R_d + R_k)}\right] \times \frac{180}{\pi}$$

where L_0 = half die width (i.e. half the distance between the centres of the rollers), R_d = the roller radius, R_k = the knife radius, and $\beta_{F\,max}$ is the bending angle at F_{max}.

[0026] Then F_{max} becomes;

$$F_{Max} = \frac{4 \cdot M_{max}}{(R_d + R_k)} \cdot \sin \beta_{F\,max} =$$

$$= \frac{4 \cdot M_{max}}{(R_d + R_k)^2} \cdot \left(L_0 - \sqrt{{L_0}^2 - (R_d + R_k)^2}\right)$$

[0027] Maximum bending moment can be estimated as;

$$M_{Max} = \frac{B \cdot t^2 \cdot \left(R_m \cdot \frac{2}{\sqrt{3}}\right)}{4}$$

where; B= length of bend (i.e. length of the sample being bent, see Figure 3b); t=thickness and R_m=ultimate strength.

[0028] Assuming a constant cross-section moment condition, it is shown by the inventor that the angle position for the natural F-maximum only depends on the geometry of the test apparatus. However, if the material displays moment-hardening behaviour, the natural peak load will appear a bit later.

[0029] Using the methods of the invention, an operator can be informed when a material passes the natural force maximum during the bending test. In some cases, i.e. for mild steel up to the level of approximately 800 MPa in strength, this natural force maximum may be reached before an apparent failure of the material in the bending test (i.e. the applied force drops during the bending test), showing the utility of the invention in determining the bending properties of materials that are not otherwise derivable using standard methodologies. The failure of standard methodologies such as the VDA 238-100 test in determining the maximum force arises due to the non-linearity of the applied force and bending angle, which is compensated for using the methodology of the present invention.

[0030] It should be noted that the method according to the present invention is not intended to replace standard tests such as VDA 238-100, but to complement them. Also there is still a need for conventional air-bending tests to determine the recommended bendability limit of a metallic material in terms of the ratio of knife radius to thickness of the metallic material, i.e. the R/t-ratio. There is however also a need for a complementary method, such as the method according to the present invention, which enables a metallic material's behaviour during bending to be investigated in connection with its microstructure. The method according to the present invention namely allows inhomogeneity within a metallic material to be detected and analysed.

[0031] According to an embodiment of the invention, the method comprises the step of estimating the Young's modulus, E, of a metallic material by plotting a graph of β_2 and the calculated cross-section moment, M and determining the gradient of the elastic part of the moment curve, whereby the gradient is:

$$\frac{2 \cdot E' \cdot I}{L_m}$$

where I is the moment of inertia and where E' is the Young's modulus in plain strain and is given by:

$$E' = \frac{E}{(1 - \nu^2)}$$

where v Poisson's ratio.

[0032] For steel, this can be expressed as:

$$E' \approx \frac{E}{(1-0.3^2)}$$

[0033] According to an embodiment of the invention, the calculated cross-section moment, M, or the calculated flow stress, σ_1, or the estimated Young's modulus, E, or the ratio M/M_e, is used to optimize a product comprising the metallic material, i.e. the calculated cross-section moment, M, or the calculated flow stress, σ_1, or the estimated Young's modulus, E, or the ratio M/M_e, is used to determine how a product utilizing the metallic material should be dimensioned, constructed and/or designed in order to withstand a particular bending force, whereby its suitability for a particular application may be ascertained.

[0034] According to an embodiment of the invention, the metallic material may be a cold-rolled or hot-rolled metallic material, such as cold-rolled steel or hot-rolled steel. The metallic material may be steel (such as a high strength steel or ultra-high strength steel), an aluminium or magnesium alloy, or comprise any other metal or metal alloy.

[0035] As used herein, "high strength steel" has a yield strength of from 250 up to 550 MPa, while "ultra high strength steel" has a yield strength of ≥ 550 MPa.

[0036] As used herein, the tensile strength is measured using ISO 6892-1 or EN 10002-1, preferably ISO 6892-1.

[0037] The moment characteristics obtained for different materials, using the invented formula, may also be super-positioned, simulating cross-section behaviour of multi-layer type of materials.

[0038] According to an embodiment of the invention, the method comprises the step of obtaining the moment-characteristic of the metallic material, i.e. the cross-section moment, M, of the metallic material, and using it to estimate the spring-back of the metallic material for a free choice of set up in bending, using the following equations:

$$\Delta\beta_{tot} = \beta_{C\,el} + \beta_{S\,el} + \Delta\beta_{12}$$

$$\beta_{C\,el} = \frac{M_L \cdot L_C}{E'I} = \frac{M_L \cdot \left(R_k + \frac{t}{2}\right) \cdot \beta_C}{2\,E'I}$$

$$\beta_{S\,el} = \frac{M_L \cdot L_S}{2\,E'I} = \frac{M_L}{2\,E'I} \cdot \frac{L_N}{\cos(\beta_1)}$$

$$\beta_C = \beta_2 - \frac{2}{M}\int \beta_2 dM$$

$$\Delta\beta_{12} = \beta_1 - \beta_2 = \int_0^{\beta_1} \frac{t \cdot \sin\beta_1}{L_m(\beta_1)}$$

$$M_L = M\frac{L_m}{L_N}$$

the approximate length of the flange at the state for unloading is:

$$\frac{L_N}{\cos(\beta_1)}$$

and the half length of metallic material in contact with the knife is:

$$\left(R_k + \frac{t}{2}\right)\cdot\beta_C$$

where:

$\Delta\beta_{tot}$ is the total amount of spring-back, β_{Sel} is spring-back of the flange, β_{Cel} is the spring-back related to material in contact with the knife, M_L is the reduced moment due to the limitation of curvature due to the knife radius, L_N is the moment arm (horizontal distance between the tangential contact points considering a curved flange), L_S is the estimated length of the flange, L_C is length of material shaped by the knife, R_k is the knife radius, and β_C is the contact angle between material and the knife and β_1 is the bending angle..

[0039] According to another embodiment of the invention the method comprises the step of obtaining the cross-section moment, M of the metallic material and using it to estimate a friction coefficient μ, of the metallic material using the equation:

$$\mu = \left[\frac{M - M_{mtrl}}{M_{mtrl}}\right]\cdot\frac{1}{\tan\beta_1}$$

where M_{mtrl} is the cross-section moment characteristics obtained for a material, using friction free bending test equipment.

[0040] The present invention also concerns a computer program product that comprises a computer program containing computer program code means arranged to cause a computer or at least one processor to execute the calculating step of a method according to an embodiment of the present invention, stored on a computer-readable medium or a carrier wave, i.e. whereby the computer program product may be used to calculate the cross-section moment, M, and/or any of the other properties of the metallic material described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0041] The present invention will hereinafter be further explained by means of non-limiting examples with reference to the appended figures where;

Figure 1
: shows a diagram used to determine the bendability of a metallic material using the VDA 238-100 standard test according to the prior art,

Figure 2
: shows the steps of a method according to an embodiment of the present invention,

Figure 3a
: schematically shows the forces and moment acting on a metallic material during bending

in a method according to an embodiment of the invention,

Figure 3b

schematically shows the positioning of the sample, rollers and bending knife, and the variables used to describe the various dimensions referred to herein,

Figure 4

shows a conventional force-curve from VDA 238-100 standard test,

Figure 5

shows a conventional moment curve calculated using the conventional formula for the moment,

Figure 6

shows the contact angle β_C at the knife that arises when the flange becomes curved during the bending test,

Figure 7

shows the moment curve, M_{tot}, calculated using the calculated cross-section moment according to the present invention,

Figure 8

shows tensile test data obtained from tests on Domex 700™,

Figure 9

shows a comparison between the calculated bending force based on Domex 700™ tensile test data and three bending tests performed on the same material with different stroke lengths,

Figure 10

schematically illustrates a coil of metallic material,

Figure 11

shows the theoretical elastic cross-section moment and the maximum cross-section moment at bending,

Figure 12

shows the force versus knife position measured at bending,

Figure 13

shows the calculated cross-section moment according to the present invention,

Figure 14

shows the calculated non-dimensional moment M/M_e,

Figure 15

shows the flow stress obtained using the calculated cross-section moment according to the present invention,

Figure 16

shows an estimation of Young's modulus obtained using a method according to the present invention,

Figure 17

shows a comparison of the ratio of M/M_e values obtained from tensile tests and bending tests,

Figure 18

shows the steps of the method for estimating spring back for a free choice of geometrical setup,

Figure 19

shows the principal for estimation of the shape of curvature of a material,

Figure 20

shows the distribution of energy within a bend,

Figure 21

shows the changes in contact and shape angles β_C and β_S respectively during bending,

Figure 22

shows the force versus the displacement calculated using a method according to the present invention, and comparisons with tests performed,

Figure 23

shows the force vectors representing the bending load and friction force during a bending test,

Figure 24

shows the moment versus the bending angle for a range of 6mm thick high strength steels subjected to bending with different levels of friction involved,

Figure 25

shows the force versus displacement for a range of 6mm thick high strength steels subjected to bending with different levels of friction involved,

Figure 26

shows a comparison between experimentally measured force and force calculated using the methods of the invention,

Figure 27

shows a comparison between the experimentally measured force and calculated angle at F_{max}, depending on the geometry of the bending setup,

Figure 28

shows the moment characteristics of the base materials used to form the composite in Example 5,

Figure 29

shows the moment curves for the various layers in the composite structure of Example 5, and

Figure 30

shows the predicted unit-free moment curve of the composite structure of example 5, in comparison to the actual curve of an equivalent thickness of DX960 base material.

DETAILED DESCRIPTION OF EMBODIMENTS

[0042] The following abbreviations are used herein:

M

= Cross-section (bending) moment

M_{Max}

= Maximum bending moment

M_L

= Reduced moment due to the limitation of curvature due to the knife radius

M_{mtrl}

= Cross-section moment characteristics obtained using friction free bending test equipment

M_1

= Component of cross-section moment M

M_2

= Component of cross-section moment M

M_{tot}

= $M_1 + M_2$

M_e

= Elastic cross-section moment

F

= Applied force

F_{max}

= Maximum applied force

S

= Vertical distance through which the bending knife has been displaced

S_x

= Horizontal movement of the contact point at the knife

S_y

= Total vertical movement of the contact point, taking account that it moves upwards along the knife surface

B

= Sample length (length of the bend, or the length of the sample in the dimension parallel to the rollers)

t

= Sample thickness

β_1

= Bend angle

β_2

= True angle to which plate is bent

$\Delta\beta_{12}$

= Difference between β_1 and β_2

β_C

= Contact angle between the metallic material and the knife

$\Delta\beta_{tot}$

= Total amount of spring-back

β_{Sel}

= Spring-back of the flange

β_{Cel}

= Spring-back related to the material in contact with the knife

$\beta_{F\,max}$

= Bend angle at F_{max}

L_0

= Half die width (i.e. half the distance between the centre point of the rollers

$L_m(\beta_1)$

= Moment arm at angle β_1 (horizontal distance between the tangential contact points)

$L_N(\beta_1, \beta_C)$

= Moment arm (horizontal distance between the real contact points at the knife and die radius, i.e. the distance between where the knife and die contact the plate being bent)

L_S

= Estimated length of the flange in contact with the knife and die

L_C

= Length of the material shaped by the knife

R_d

= Roller radius

R_k

= Knife radius

R_m

= Ultimate strength

σ_1

= Flow stress (plain strain)

σ

= Effective stress

ε_1

= Main strain (plain strain

ε

= Effective strain

E

= Young's modulus

E'

= Young's modulus in plain strain

I

= Moment of inertia

μ

= Friction coefficient of the metallic material

μ_d

= Friction between the metallic material and the roller radius

v

= Poisson's ratio

[0043] By "simply supported" is meant that each end of the plate can freely rotate, therefore each end support has no bending moment. This is achieved by supporting the plate with parallel rollers, such that the moment created by the knife when the external force is applied is balanced by the moment created along the centre line where the bending takes place, and no additional bending or force dissipation takes place at the point of contact between the plate and the rollers.

[0044] Typically, the plate is substantially horizontal when provided on the rollers. By "substantially horizontal" is meant that the plate does not move due to gravity when balanced on the rollers prior to bending. In practice, the plate will typically be horizontal, though the skilled person would understand that very small variations from horizontal can also be used, providing the force applied by the bending knife is in a plane perpendicular to the plane formed by the centres of the rollers and which intersects the plate along the entire length of the centre line between the rollers. In other words, if the plate is e.g. 2 degrees from horizontal when the test begins, the bending knife moves (and consequently applies the force) in a direction the same amount (2 degrees) from vertical during the test, such that the bending force is applied perpendicular to the plate's starting position.

[0045] The bending force is applied across the entire length of the plate. This ensures that the plate is bent evenly during the test and the force resisting the knife corresponds to the bending moment of the metallic material, rather than internal forces arising due to buckling of the plate. To ensure the bending force is applied across the entire length of the plate, the length of the bending knife typically is greater than the platelength. Typically, the bending knife extends beyond the edge of the plate during bending. Due to the end-effects, i.e. not plain-strain condition, the knife will however not be in contact with the material close to the edges. Therefore, the length of the specimen should be at least 10 times the thickness, to ensure the main response of plain strain condition.

[0046] The plate is typically positioned such that cutting burs or fracture surface portions, possibly existing at the edges, are located on the knife side (i.e. on the sample side which will be under compression during bending).

[0047] Figure 1 shows a diagram used to determine the bendability of a metallic material using the VDA 238-100 standard test according to the prior art in which the bendability of the metallic material is determined by measuring the knife position, S at the maximum applied bending force, F_{max}.

[0048] Figure 2 shows the steps of an exemplary method according to an embodiment of the present invention. The method comprises the steps of carrying out a plate bending test according to the VDA 238-100 standard, and calculating a cross-section moment, M, of said metallic material using the following equation:

$F \cdot Im(R_{\cdot})$

$M = \frac{F \cdot Lm(\beta_1)}{2 \cdot cos^2(\beta_1)}$

where F is the applied bending force, Lm(β_1) is the moment arm, and β_1 is the bending angle. The calculated cross-section moment, M, may be used to predict a real response of the metallic material during bending.

[0049] This improved method for characterizing a metallic material was found by studying the energy balance expression:

$$\int F\, ds = \int 2M d\beta_2 \qquad \ldots(1)$$

[0050] Where F is the applied force, S is the knife position, M is the moment of the metallic material test specimen and β_2 is the true bending angle.

[0051] This expression indicates that there has to be a balance between the energy input during air bending and the energy absorbed by the test specimen. Friction between the material and the roller radius, μ_d, is assumed to be negligible.

[0052] Figure 3a shows the forces and moment acting on the metallic material test specimen 10 during bending. $L_m(\beta_1)$ is the moment arm that will start with the initial value of L_0 (which is half of the die width) and will decrease during the stroke. The bending angle, β_1, is half of the real bending angle.

[0053] Figure 4 shows a typical force diagram from a VDA 238-100 standard test showing the applied force, F and the vertical displacement of the knife, S.

[0054] The vertical displacement of the knife, S can be expressed geometrically as a function of the bending angle β1 as:

$$S(\beta_1) = L_0 \cdot tan(\beta_1) + (R_d + R_k + t) \cdot (1 - \frac{1}{\cos(\beta 1)}) \qquad \ldots(2)$$

[0055] By applying the conventional expression from the literature to calculate the cross-section moment,

i.e. $= \frac{F \cdot L_m(\beta_1)}{2}$,

and also converting the distance S to the corresponding bending angle β_1, then the plot of cross-section moment, M, versus the bending angle, β_1, will have the form shown in Figure 5.

[0056] It was observed by the inventor that there is a mismatch between the energy input, $\int F\, ds$, during bending and the internal momentum and its energy, $\int 2Md\beta_1$, i.e. if applying the common expression for the momentum,

$M = \frac{F \cdot L_m(\beta_1)}{2}$

is used (as shown in Figure 5). The cross-section moment in bending, referring to the literature, should rather be constant after complete plastification.

[0057] The inventor thereby found that:

$$\int F\,ds \neq \int \frac{F \cdot L_m(\beta_1)}{2} 2d\beta_1$$

[0058] Reasonably, it must be a relationship between the travel distance of the knife, S, and the bending angle, β_1, that gives the correct expression and thereby achieves an energy-balance. By investigating the non-linearity between S and β_1, the true relationship between the applied force, F, and the cross-section, M , was derived by the inventor, as follows.

[0059] Taking the first derivative of the geometrical function, equation (2) gives:

$$\frac{dS}{d\beta 1} = \frac{L_0-(R_k+R_d+t)\cdot Sin(\beta 1\,)}{Cos(\beta 1)^2} = \frac{L_e}{Cos(\beta 1)^2}$$

...(3)

[0060] The following function:

$L_e = L_0 - (R_k + R_d + t) \cdot \sin(\beta_1)$

L_e is almost equal to the moment-arm in bending, except for the material thickness, t.

[0061] Geometrically, the real moment-arm is (see Figure 3a):

$$L_m(\beta_1) = L_0 - (R_k + R_d) \cdot Sin(\beta_1)$$

[0062] The energy balance expression, equation (1), can then be expressed as follows using the derivative, equation (3):

$$\int F \cdot ds = \int M \cdot 2\frac{d\beta_2}{d\beta_1} \cdot d\beta_1 = \int M \cdot 2\frac{d\beta_2}{d\beta_1} \cdot \frac{d\beta_1}{dS} dS$$

$$\Rightarrow \quad F = M \cdot 2\frac{d\beta_2}{d\beta_1} \cdot \frac{d\beta_1}{dS} = M \cdot 2\frac{d\beta_2}{d\beta_1} \cdot \frac{Cos(\beta 1)^2}{L_e}$$

[0063] Here a new angle, β_2, has been introduced, i.e. the real angle that will be at the bend due to the energy balance, and which is different from the geometrical bending angle, β_1, applied, see Figure 3a. For small bending angles, β_1, it is true that the cross-section moment, M, is equal to

$\frac{F \cdot L_m(\beta_1)}{2}$,

called M_1 herein.

[0064] Assuming that for large bending angles, the total moment, M_{tot}, is a sum of M_1 and M_2 where M_2 is an unknown function but is assumed to be a multiple of function M_1, M_{tot} can be expressed as follows:

$$M_{tot} = M_1 + M_1 \times f(\beta_1) = M_1 \times \left(1 + f(\beta_1)\right) = \frac{F \cdot Lm(\beta 1)}{2} \times \left(1 + f(\beta_1)\right)$$

[0065] In order to balance the energy balance expression, the ratio:

$$\frac{d\beta_2}{d\beta_1}$$

is assumed to be equal to:

$$\frac{L_e}{L_m}$$

which gives:

$$F = \frac{F \cdot Lm(\beta 1)}{2} \times \left(1 + f(\beta_1)\right) \cdot 2 \frac{L_e(\beta 1)}{L_m(\beta 1)} \cdot \frac{Cos(\beta 1)^2}{L_e(\beta 1)}$$

Hence;

$$\mathrm{F} = F \cdot Cos(\beta_1)^2 \times \left(1 + f(\beta_1)\right)$$

[0066] It follows that:

$$f(\beta_1) = Tan(\beta_1)^2,$$

$$(\mathrm{i.e.}\quad \frac{1}{\mathrm{Cos}^2(\beta)} = 1 + \mathrm{Tan}^2(\beta)\ )$$

[0067] Finally, the expression for the cross-section moment, M, will then become:

$$M = \frac{F \cdot Lm(\beta_1)}{2 \cdot cos^2(\beta_1)}$$

[0068] This correct formulation of the cross-section moment, M, which more accurately predicts the bending behaviour of metallic materials, is even valid for large bending angles (i.e. angles greater than 6°).

[0069] Figure 6 shows the total moment, M_{tot} as a sum of M_1 and M_2. The common expression, M_1 is valid only for small bending angles (i.e. angles up to about 6°). The angle β_2 is the true angle that the material is bent to, not the same as the bending angle, β_1 applied.

[0070] It can be theoretically confirmed that this invented solution is also valid even if the flange becomes curved, i.e. the contact point will occur at the angle of β_C instead of β_1 (see Figure 6), as is usually the case during bending. Thus:

$$M = \frac{d}{d\beta_2}\left[\frac{Energy}{2}\right] = \frac{d}{d\beta_1}\left[\int \frac{F_y}{2} \cdot \frac{dS_y}{d\beta_1} d\beta_1 + \int \frac{F_x}{2} \cdot \frac{dS_x}{d\beta_1} d\beta_1\right] \cdot \frac{d\beta_1}{d\beta_2} =$$

$$= \frac{d}{d\beta_1}\left[\int \frac{F_y}{2} \cdot \frac{dS_y}{d\beta_1} d\beta_1 + \int \frac{F_y}{2} \tan\beta_C \cdot \frac{dS_x}{d\beta_1} d\beta_1\right] \cdot \frac{L_m}{L_e} =$$

$$= \frac{F_y}{2} \cdot \left[\frac{dS_y}{d\beta_1} + \tan\beta_C \cdot \frac{dS_x}{d\beta_1}\right] \cdot \frac{L_m}{L_e}$$

[0071] Where the movements of the contact-point is described by;

$$\frac{dS_y}{d\beta_1} = \frac{d}{d\beta_1}[S - R_k \cdot (1 - \cos\beta_C)] = \frac{L_e}{\cos^2\beta_1} - R_k \sin\beta_C \cdot \frac{d\beta_C}{d\beta_1}$$

$$\frac{dS_x}{d\beta_1} = \frac{d}{d\beta_1}[R_k \cdot \sin\beta_C] = R_k \cos\beta_C \cdot \frac{d\beta_C}{d\beta_1}$$

[0072] S, is the vertical knife-movement, S_x is the horizontal movement of the contact point at the knife, and S_y is the total vertical movement of the contact-point, taking into account that it moves upwards along the knife surface.

[0073] Hence;

$$M = \frac{F_y}{2} \cdot \frac{L_e}{\cos^2\beta_1} \cdot \frac{L_m}{L_e} = \frac{F_y}{2} \cdot \frac{L_m}{\cos^2\beta_1}$$

[0074] The present invention also comprises a carrier containing a computer program code means that, when executed a computer or on at least one processor, causes the computer or at least one processor to carry out the method according to an embodiment of the present invention (i.e. whereby the computer program code means may be used to calculate the cross-section moment, M, and/or any of the other properties of the metallic material described herein), wherein the carrier is one of an electronic signal, optical signal, radio signal or computer readable storage medium.

[0075] Typical computer readable storage media include electronic memory such as RAM, ROM, flash memory, magnetic tape, CD-ROM, DVD, Blueray disc etc.

[0076] The present invention further comprises a computer program product comprising software instructions that, when executed in a processor, performs the calculating step of a method according to an embodiment of the present invention.

[0077] The present invention further comprises an apparatus comprising a first module configured to perform the calculating step of a method according to an embodiment of the present invention, and optionally a second module configured to perform the calculating step of a method according to a further embodiment of the present invention.

[0078] For example, the first module may be configured to perform a calculating step to calculate the cross-section moment M, with the optional second module configured to perform a calculating step to calculate a further property of the metallic material, such as the flow stress, main strain etc..

[0079] The invention further relates to a method in which said calculated cross-section moment, M, or the calculated flow stress, σ_1, or the estimated Young's modulus, E, or the ratio M/M_e, or other property calculated using the methods disclosed herein, is used to optimize a product comprising said metallic material.

[0080] The dimensionless ratio M/M_e described further in Example 2 is particularly useful, as it shows the point at which a material becomes unstable during bending. Specifically, when M/M_e is below 1.5, the material is stable during bending. When M/M_e reaches the level of 1.5, the material becomes unstable and by that close to failure.

[0081] The invention therefore relates to a method for determining the conditions under which M/M_e remains below 1.5 for a given material. With knowledge of these conditions, the skilled person is able to ascertain the suitability of a particular material to a given application. For instance, the skilled person can easily ascertain whether a material is capable of being bent into a desired configuration without failure, allowing the suitability of the material to be predicted without extensive testing. This method may therefore comprise a further step of utilizing the material as a structural element in a composite product, characterized in that the material is bent under conditions wherein the ratio of M/M_e is below 1.5 during the manufacture of the composite product.

[0082] The invention also relates to a method for determining the point at which a metallic material becomes unstable during bending, said method comprising determining the point at which the ratio M/M_e becomes 1.5.

[0083] The method may also be used to evaluate different metallic materials to determine which materials have bending properties that meet predetermined values necessary for a certain use.

[0084] Advantageously, the moment characteristics obtained for different materials may also be super-positioned, allowing the cross-section behaviour of multi-layer materials to be predicted. In this way, the skilled person is able to use the methodology of the invention to design new composite materials, and to predict the bending properties of multi-layer materials based on knowledge of the individual layers.

[0085] For instance, high strength metallic materials such as high strength steel often have poor bending properties. Adding a layer of more ductile, lower strength material can provide composite materials with improved bending properties. Using the methodology of the invention, the skilled person can, without undue experimentation, determine what type of material is required in order to provide the desired bending properties to the high strength material.

[0086] Further details of how the moment characteristics for different materials may be super-positioned are provided in Example 5.

[0087] The method may also be used to evaluate plates of the same metallic material having different thicknesses, e.g. by studying the ratio of M/M_e.

[0088] The following examples implement the methodology of the invention to investigate and characterise the properties of various steels during bending.

Example 1

[0089] To confirm the correctness of the new expression for the cross-section moment, M, the bending force, F, was calculated using tensile-stress data. The metallic material investigated was: Domex 700 MC™, a high strength hot-rolled steel having a thickness of 2.1 mm. Bending data: Die width L_o= 70.5 mm, knife radius R_k=16 mm and roller-radius Rd= 25 mm.

[0090] The tensile-data is:

$\bar{\sigma}(\bar{\varepsilon})$

[0091] Converting tensile data to flow stress and plain strain, as:

$$\sigma_1 = \frac{2}{\sqrt{3}} \cdot \bar{\sigma} \text{ and } \varepsilon_1 = \bar{\varepsilon} \cdot \frac{\sqrt{3}}{2}$$

assuming that

$$\beta_2 \approx \beta_1 \; (as\; \beta_2 = \beta_1 - \int \frac{t \cdot \sin \beta_1}{L} \; and\; L \gg t)$$

then let;

$$L_m\left(\beta_{2\,(i=0)} = 0\right) = L_0 \text{ and } \beta_{2\,(i+1)} = \varepsilon_{1\,(i+1)} \cdot \frac{L_m(\beta_{2\,(i)})}{t}$$

[0092] The expression for the total moment, M, can then be written as:

$$M = 2 \cdot B \cdot R^2 \int \sigma_1 \cdot \varepsilon_1 \cdot d\varepsilon \; = \frac{B \cdot t^2}{2 \cdot \varepsilon_1^2} \int \sigma_1 \cdot \varepsilon_1 \cdot d\varepsilon \; = \frac{B \cdot t^2}{2 \cdot \varepsilon_1^2} \int \frac{2}{\sqrt{3}} \bar{\sigma} \cdot \varepsilon_1 \cdot d\varepsilon_1$$

...(4)

[0093] Combining it with the invented expression:

$$M = \frac{F \cdot L_m(\beta_1)}{2 \cdot cos^2(\beta_1)} \; and\; set\; \beta_2 = \beta_1$$

then the force, F, becomes;

$$F = \frac{2 \cdot \cos^2(\beta_2)}{L_m(\beta_2)} \cdot \frac{B \cdot t^2}{2 \cdot \varepsilon_1{}^2} \int \frac{2}{\sqrt{3}} \bar{\sigma} \cdot \varepsilon_1 \cdot d\varepsilon_1$$

[0094] The relationship between bending angle, β_2, and the knife position, S, is given by:

$$\frac{dS}{d\beta_2} = \frac{dS}{d\beta_1} \cdot \frac{d\beta_1}{d\beta_2} \approx \frac{L_e}{\cos^2(\beta_2)} \cdot \frac{L_m}{L_e} = \frac{L_m}{\cos^2(\beta_2)}$$

[0095] Hence:

$$S \approx \int \frac{L_m(\beta_2)}{\cos^2(\beta_2)} \cdot d\beta_2$$

[0096] By using the tensile data, shown in Figure 8, an estimation of the bending force can then be obtained, (see figure 8), which confirms the correctness of the invented expression for the cross-section moment, M.

[0097] Figure 9 shows a comparison between the calculated bending force (curve 12) based on tensile test data and three individual bending tests performed on the same material but with different stroke length, S. The right-hand sides of the three bending test curves represent the unloading. The bending line was placed along the rolling direction (RD) and the tensile test data was performed perpendicular to the rolling direction (TD).

[0098] Figure 10 schematically illustrates a coil of hot-rolled steel product 10 from which samples may be cut for a bending test. Bending tests may be performed in both the rolling (RD) direction and in a direction transverse to rolling (TD). Additionally, tests can also preferably be performed by turning the samples with rolling-mill side up and down verifying the symmetry of the textures. Figure 10 shows the bend orientation with respect to a coil of hot-rolled steel product 10.

[0099] This example showed that the metallic material 10 has a similar behaviour during a bending test and a tensile test. As a tensile test is an average value of the cross-section properties, compared to bending where the properties are "scanned" from outer surface and inwards, this case shows that the metallic material 10 behaved uniformly throughout its thickness. Furthermore, Figure 9 shows that the force drops naturally, and not because of any failures in this case, which illustrates the shortcomings in the VDA 238-100 standard test.

Example 2

[0100] In this example a non-dimensional moment (as described in the publication entitled "Plastic Bending- Theory and Application" by T.X. You and L.C. Zhang, ISBN 981022267X) will be exemplified. The non-dimensional moment may be derived by the ratio between the maximum cross-section moment, M_{max}, and the elastic cross-section moment; M_e. This ratio has two limits; a lower limit that is equal to 1.0 and an upper limit equal to 1.5. The first case is when the material is deformed elastically; the latter case is the state that the material reaches at its absolute maximum moment. Previously, it has not been possible to obtain the material plastification characteristics in between these limits. Figure 11 shows the equations representing these two limits, i.e. the theoretical elastic cross-section moment, M_e and the maximum cross-section moment, M_{max}, at bending, and also schematic drawings of the stress distributions in the both cases.

[0101] The lower and upper limits of the ratio are as follows, using the two equations shown in Figure 11:

$$\frac{M_e}{M_e} = 1.0 \qquad \frac{M_{max}}{M_e} = \frac{6}{4} = 1.5$$

[0102] However, to get the entire metallic material response in the whole interval from the elastic state up to the maximum load-carrying capacity, the expression is written as:

$$1 \leq \frac{M(\beta_2)}{M_e(\beta_2)} \leq 1.5$$

where $M(\beta_2)$ is the new invented function.

[0103] The metallic material 10 that was investigated in this example was: Docol 1180 DP™, a high strength cold-reduced dual phase grade steel having a thickness of 1.43 mm.

[0104] Figure 12 shows the applied force versus the knife position S during bending in a VDA 238-100 standard test. From the bending test, the responses were obtained by measuring the force applied and the position of the knife. The material was tested in both transverse (TD) direction and along the rolling direction (RD). Then the force was transformed to the calculated cross-section moment, M, using the new invented expression, see Figure 13. The angle β_2, was obtained by subtracting the fault angle, $\Delta\beta_2$, (which is important to take into account when calculating the spring back, i.e. over-bending angle) from the β_1, bending angle applied, calculated as indicated below:

Using the relationship based on the condition for energy equilibrium:

$$\frac{d\beta_2}{d\beta_1} = \frac{L_e}{L_m}$$

[0105] Then β_2 can be obtained from the integral:

$$\beta_2 = \int \frac{L_e}{L_m}\, d\beta_1 = \beta_1 - \int \frac{t \cdot Sin(\beta_1)}{L_m(\beta_1)}\, d\beta_1 = \beta_1 - \Delta\beta_2$$

where β_1 is calculated using equation (2).

[0106] The ratio M/M_e was derived by the inventor as:

$$\frac{M}{M_e} = \frac{3}{\left(\left(\frac{dM}{d\beta_2} \Big/ \frac{M}{\beta} \right) + 2 \right)}$$

$$\left(\left(\cdot \beta_2\right) \right)$$

...(5)

[0107] The expression can easily be verified for the elastic part of deformation, as the derivative
$\frac{dM}{d\beta_2}$,
is equal to the ratio
$\frac{M}{\beta_2}$,
i.e.
$(\frac{2E'I}{L_m})$
making the ratio equal to 1.0.

[0108] When the derivative
$\frac{dM}{d\beta_2} = 0$
then the ratio will become equal to 1.5. This means that when the moment M drops, the material is failing or strain is localized.,

[0109] By applying equation (5) in this example, the calculated non-dimensional moment diagram, M/M_e will be as shown in Figure 14.

[0110] The flow stress can also be obtained from the moment derived from equation (4):

$$\sigma_1 = \frac{2}{B \cdot t^2 \cdot \varepsilon_1} \cdot \frac{d}{d\varepsilon_1}(M \cdot \varepsilon_1{}^2)$$

[0111] Where the main strain, ε_1 is calculated from:

$$\varepsilon_1 = \beta_2 \cdot \frac{t}{L_m(\beta_1)}$$

[0112] Figure 15 shows a plot of the flow stresses versus main strain, ε_1.

[0113] Using the method according to the present invention makes it possible to use a metallic material's bending behaviour to estimate the metallic material's Young's modulus, E.

[0114] Young's modulus in plain strain, E', is given by:

$$E' = \frac{E}{(1 - \nu^2)}$$

[0115] For steel, this can be expressed as:

$$E' \approx \frac{E}{(1-0.3^2)}$$

[0116] In this example, Young's modulus was given by:

$2.18 \cdot 10^5 MPa$ Figure 16 shows a graph of main strain, ε_1 versus flow stress, σ_1,

[0117] Another way of obtaining Young's modulus, E is by determining the gradient of the elastic part of the moment curve (such as that shown in Figure 13), whereby the gradient is:

$$\left(\frac{2 \cdot E' \cdot I}{L_m}\right)$$

[0118] The relationship between effective stress and strain, flow stress, σ_1 can be converted using the following expressions, assuming plain strain conditions:

$$\bar{\sigma} = \frac{\sqrt{3}}{2} \cdot \sigma_1 \text{ and } \bar{\varepsilon} = \frac{2}{\sqrt{3}} \cdot \varepsilon_1$$

and converting to true values using

$$\sigma_{tr} = \bar{\sigma} \cdot (1 + \bar{\varepsilon}) \text{ and } \varepsilon_{tr} = \bar{\varepsilon} \cdot LN(1 + \bar{\varepsilon})$$

[0119] It is even possible to plot and compare the graph with tensile test data. This will indicate how the hardening behaviour should act if the metallic material's properties are the same from its surface to its centre. If the results of the deformation mechanisms in bending and during pure tension are similar, this is evidence that the metallic material is homogeneous throughout its thickness.

[0120] To define the M/M_e ration from tensile data, the following derived expression is used:

$$\frac{M}{M_e} = \frac{\frac{B \cdot t^2}{2 \cdot \varepsilon_1{}^2} \int \sigma_1 \cdot \varepsilon_1 \cdot d\varepsilon_1}{\frac{B \cdot t^2 \cdot \sigma_1}{6}} = \frac{3}{\sigma_1 \cdot \varepsilon_1^2} \int \sigma_1 \cdot \varepsilon_1 \cdot d\varepsilon_1 = \frac{3}{\bar{\sigma} \cdot \bar{\varepsilon}^2} \int \bar{\sigma} \cdot \bar{\varepsilon} \cdot d\bar{\varepsilon}$$

[0121] Figure 17 shows a comparison between a tensile test and bending tests. In the illustrated case the metallic material seems to harden approximately in similar way, comparing bending and uniform stretching.

[0122] According to an embodiment of the invention, the method comprises the step of obtaining a cross-section moment, M, of a metallic material and using it to estimate the spring-back for a free choice of set up in bending.

[0123] When bending, spring-back is always compensated for by making a certain number of degrees of "over-bending" to get the final degree of bend. It is difficult to estimate the amount of degrees of "over-bending" to finally get the desired bend. When handling a material such as high strength steel, it is even more complicated as the spring-back behaviour is higher compared to a material such as mild steel. A thin (3.2 mm) Ultra High Strength Steel (Hardox 450) was used to investigate the spring-back-effect in four cases of setup for bending. The ultimate strength for Hardox 450 was approximately 1400-1450 MPa.

[0124] The method comprises three steps, see Figure 18: In the first step the material is tested to determine the material-characteristics in bending, e.g. by performing a VDA 238-100 standard test type of bending, i.e. friction free bending, obtaining a fully plastified cross-section. In the second step, the moment curve is transformed regarding geometry of a free choice of geometrical setup for a certain case in bending. In the third step these data are used to calculate the spring-back. Even thickness can be converted from the material that has been investigated in the first step. The most accurate result is obtained when using same batch of material in the first and second steps, due to differences in material characteristics.

[0125] Material characteristics are obtained by performing the VDA 238-100 standard test, or another type of friction free bending equipment, giving a "thumb-print" of a current material, by obtaining a moment-curve vs angle diagram. When testing the material characteristics, a narrow die-width is used and a small radius of the knife, approximately 0.7*t for thicker hot-rolled material. The roller radii are friction free, i.e. able to rotate. The maximal bending angle (half bending angle, β1) should not be more than 30-35°, eliminating every kind of friction adding a fault energy not connected to the material behaviour.

[0126] By using a method according to the present invention, a moment-diagram, such as the moment-diagram shown in Figure 13, can be obtained, based on the measured force vs knife-position, such as the diagram shown in Figure 4, and the geometry for the trial-setup.

[0127] R_d representing the roller radius may for example be 40.0 mm, the knife radius may be 2.0 mm, t (the material thickness) may be 3.2 mm, L_0 the half die-width may be 46 mm and finally, B, the length of the material (i.e. bending length) may be 75 mm.

[0128] It was found by the inventor that if the knife-radius is larger in relation to material thickness and if an increased die-width (compared to the VDA 238-100 standard test) is used, the material between the supports, i.e. the knife and rollers, will be subjected to a curvature, see dashed curve in Figures 19 and 20. This means the contact between the knife and the material will not be at the tangent point of a straight line, instead at angle, βc, rather than at β_1, resulting in a moment arm, L_N, that is longer compared to L_m (see Figure 19). To be able to estimate the reduced cross-section moment, M_L, the real point of contact has to be defined. Then, the curvature must be obtained. It is noticed from literature that the shape or curvature of the material (between the contact-points, knife and rollers) is proportional to the complimentary energy, see the shaded area of Figure 19.

[0129] The inventor has found that by studying the entire distribution of energy within a bend (which is illustrated in Figure 20), the following expression for the contact-angle, *βc*, can be obtained:

$$\beta_C = \beta_2 - \frac{2}{M}\int \beta_2 dM$$

[0130] The contact angle, *βc*, is approximately equal to 0 during elastic deformation, see Figure 21. This can be shown and confirmed using the integral for the curvature angle, *βc*, putting in the expression for the elastic moment. The contact angle, *βc*, therefore starts to increase at the moment when the bend gets plastified. In Figure 21, the dotted curve represents the bending angle, the dashed curve represents true bending angle, the dash-dot curve represents the contact angle between knife and material and finally the solid curve represents the shape angle of the flange.

[0131] The expression for the real moment-arm, L_m, given on page 16 may be used when the knife radius is small, i.e. typically 0.7 times the material thickness or less (i.e. $R_k \leq 0.7t$). However, when considering a large knife radius, it is evident that the material will not make contact with the knife at the tangent for a straight line, but at angle, *βc*, shown in Figure 19. In such a case, the moment arm, L_N, will be:

$$L_N = L_0 - R_d \cdot \sin(\beta_1) - R_k . \sin \beta_C$$

[0132] It is evident that for large knife-radii, the strain will stop increasing when the material starts to follow the curvature of the knife. At that moment the strain becomes constant and will be limited by the knife-radius, even though the bending angle is increasing. It was found by the inventor that this level of strain is possible to calculate by applying the contact angle, *β*c, earlier obtained.

[0133] For free bending where the knife radius is small compared to material thickness, the bend radius will become free to decrease without any limitation. The cross-section of moment, *M,* will thereby finally reach its maximum, i.e. fully plastified. If a large knife radius is used, the bending radius will become limited by the knife's geometry, thus the cross-section of moment, M, will be reduced to a certain level, M_L.

[0134] The inventor assumed the following, as the moment is a linearly dependent with respect to the horizontal axis, L (again with reference to Figures 19 and 20);

$$\frac{L_m}{L_N} = \frac{M_L}{M} \quad => \quad M_L = M \cdot \frac{L_m}{L_N}$$

[0135] Where M is the fully, maximal moment that the material can achieve (transformed geometrically from the reference friction free test) . M_L is the moment, limited by the knife radius, representing the case to be simulated.

[0136] If a small knife radius is used, then the contact point movement is negligible, in relation to the length of the moment arm, resulting in; $M_L \approx M$. However, if a large knife-radius is used then there will be a difference between the full moment and M_L as they are positioned at two different cross-sections, along the *L*-axis, hence a difference between L_N and Lm.

[0137] The expression for calculating the bending force, F was derived to be:

$$F = \frac{2M\cos^2(\beta_1)}{L_N} = \frac{2M\cos^2(\beta_1)}{[L_0 - R_d \cdot \sin(\beta_1) - R_k \cdot \sin\beta_C]} = \frac{2M\cos^2(\beta_1)}{\left[L_0 - R_d \cdot \sin(\beta_1) - R_k \cdot \sin\left[\beta_2 - \frac{1}{M}\int 2\beta_2 dM\right]\right]}$$

where L_0 = the half die-width, R_k = knife radius, R_d = roller radius, β_1= bending angle [rad], β_2 = true bending angle [rad] transformed geometrically from the reference test, *M*= the full-moment, obtained from the reference test and transformed geometrically.

[0138] It is possible to estimate the spring back, $\Delta\beta$ *tot,* in a very accurate manner using the following equations:

$$\Delta\beta_{tot} = \beta_{C\,el} + \beta_{S\,el} + \Delta\beta_{12}$$

$$\beta_{C\,el} = \frac{M_L \cdot L_C}{E'I} = \frac{M_L \cdot \left(R_k + \frac{t}{2}\right) \cdot \beta_C}{2\,E'I}$$

$$\beta_{S\,el} = \frac{M_L \cdot L_S}{2\,E'I} = \frac{M_L}{2\,E'I} \cdot \frac{L_N}{\cos(\beta_1)}$$

Where

$$E' = \frac{E}{(1 - \nu^2)}$$

where v is Poisson's ratio and E, is the Young's-modulus

[0139] For steel, this can be expressed as:

$$E' \approx \frac{E}{(1 - 0.3^2)}$$

[0140] Furthermore,

$$\Delta\beta_{12} = \beta_1 - \beta_2 = \int_0^{\beta_1} \frac{t \cdot \sin\beta_1}{L_m}$$

$$M_L = M\frac{L_m}{L_N}$$

[0141] The approximate length of the flange being tested is:

$$\frac{L_N}{\cos(\beta_1)}$$

and the length (along the neutral layer) of the material in contact with the knife is:

$$\left(R_k + \frac{t}{2}\right) \cdot \beta_C$$

[0142] Figure 22 shows the measured force versus displacement plus the curve obtained from a friction free bending. The dotted and dashed lines in Figure 22 represent forces calculated using a method according to the present invention and using data from the reference bending test performed similar to the VDA 238-100 standard (i.e. the high load curve in Figure 22). The solid lines represent actual measured values. It can be seen that using a method according to the present invention, substantially the exact bending force can be obtained using data from a reference-test as input. It was found that results obtained from the calculation of spring-back using a method according to the present invention were in very good agreement with performed tests.

[0143] According to an embodiment of the invention the method comprises the step of obtaining a cross-section moment, M of the metallic material by carrying out a friction-free bending test according to the VDA 238-100 standard, or a similar friction free bending-test, and using the cross-section moment, M to estimate a friction coefficient of the metallic material, whereby a friction coefficient can be determined during production.

[0144] The bending force and knife position must be measured during the entire bending cycle. If the bending force increases more than what the metallic material is able to absorb in the form of energy (plastic and elastic energy), this has to be due to friction. By studying the cross-section moment behaviour of a metallic material it is thereby possible to isolate the energy-loss related to friction. It is therefore also possible to estimate the friction coefficient of the metallic material. Such a method can thereby be used not only to estimate the friction of coefficient of a metallic material in production, but also to determine coefficients of friction in general, using a dummy material with well-known behavior as a base for bending, and adding layers of materials whose friction properties are to be investigated.

[0145] Figure 23 shows the force vectors representing the bending load during a bending test. The cross-section moment, M, will make a normal force, F_N against the roller radius, hence a friction force will be developed. The vertical force vector F_y acting and measured during bending is shown in Figure 23 and corresponds to the bending force.

[0146] The friction coefficient, μ, is calculated using the following equation:

$$\mu = \left[\frac{M - M_{mtrl}}{M_{mtrl}}\right] \cdot \frac{1}{\tan \beta_1}$$

where

$$M_{Measured} = \frac{F_{y\,TOT} \cdot L_m}{2} \frac{1}{\cos^2 \beta_1}$$

and the total force acting vertically is:

$$F_{y\,TOT} = \frac{M_{mtrl}}{L_m} \cos^2 \beta_1 + \frac{M_{mtrl}}{L_m} \cos \beta_1 \cdot \mu \cdot \sin \beta_1$$

hence;

$$\mu = \left[\frac{M_{Measured} - M_{mtrl}}{\cdots}\right] \cdot \frac{1}{\cdots}$$

$$\lfloor \quad M_{mtrl} \quad \rfloor \tan\beta_1$$

[0147] Where the parameter, $M_{Measured}$, is the moment-characteristics obtained from a test where friction is involved. M_{mtrl} is the reference characteristics of the material, obtained from a friction-free test. However, as the moment characteristics is almost constant after full plastification, this parameter can be set to constant, see thick solid line in Figure 24.

Example 3

[0148] A number of bending tests were performed on hot-rolled high strength steel, 6 mm, with different conditions, i.e. low friction and extremely high, playing without or with different lubricants using same type of material in all cases. In Figure 25, the force curves are shown. By converting the forces to the cross-section moment, by using the invented expression, the influence of friction becomes more obvious, see Figure 24 and possible to evaluate by the invented expression for estimation of the friction coefficient.

Example 4

[0149] Comparison has been done between bending tests verifying the invented formula. Within the test-series, different materials, thicknesses and geometrical tooling-setups are used. In Figure 26, a good correlation between tests and invented formula can be seen. Figure 27 shows the comparison between the experimentally measured force (F_{max}) and the calculated angle at F_{max}. In these data, B/t are between 12 and 67.

[0150] Regarding scattering, no friction is assumed in the model. The ultimate strength of the materials bent is not verified.

Example 5

[0151] This Example provides a demonstration of how the moment characteristics of composite materials may be calculated based on the characteristics of its component materials. Thus, the properties of a material formed from 5 mm of DX960 (i.e. base layer or the substrate material) and 1 mm skin-layer material made of DX355 (both forms of steel) can be predicted based on the moment characteristics of the individual materials.

[0152] Both strain and moment can be transformed, using the following equations:

$$\varepsilon_{Base\ material} = \varepsilon_{Measured} \cdot \frac{t_{Base\ material}}{t_{Measured}}$$

[0153] The moment per length unit:

$$M/_B = \frac{M_{Measured}}{B} \cdot \frac{(t_{Base\ Material})^2}{(t_{Measured})^2}$$

[0154] Figure 28 shows a plot of the moment characteristics of the base materials, with DX355 being measured at t = 4 mm and scaled up to t = 6 mm. From Figure 28, it can be seen that DX355 has much larger deformation-hardening behaviour, which is preferable from a bendability performance point of view.

[0155] To calculate the moment contribution from a 1 mm skin layer of DX355 together with 5 mm DX960 (i.e. two skin layers of 0.5 mm DX355 either side of a 5 mm core of DX960), the following calculations are used:

$$M/_{B_{Layer}} = \left[M/_{B_{Layer\ 6mm}} - M/_{B_{Layer\ 6mm}} \cdot \frac{(t_{measured} - t_{Layer})^2}{(t_{measured})^2} \right] =$$

$$= \left[M/_{B_{Layer\ 6mm}} \cdot \left(1 - \frac{(6.0-1.0)^2}{(6.0)^2}\right) \right]$$

[0156] Thus, the moment-characteristics of the full thickness material, t_{full}, minus the moment-characteristics for the reduced thickness, t_{full} - t_{layer}, provides the moment-impact (or contribution) of the skin layers.

[0157] The thickness of the substrate (or base material) will in this case be:

$$t_{full} - t_{layer} = 6.0 - 1.0 = 5.0\ mm$$

[0158] Using the above expressions, this gives:

$$M/_{B_{Substrate}} = M/_{B_{Substrate\ 6mm}} \cdot \frac{(t_{measured} - t_{layer})^2}{(t_{measured})^2} = M/_{B_{Substrate\ 6mm}} \cdot \frac{(6.0 - 1.0)^2}{(6.0)^2}$$

[0159] The moment-characteristics for the for the skin layer, base layer and composite are shown in Figure 29.

[0160] Figure 30 shows the unit-free moment curves for the original DX960 material and the predicted properties of the composite material having 5 mm DX960 and two 0.5 mm skin layers of DX355. As can be seen, the composite material is predicted to have unit-free moment of below 1.5 for higher strains, which means that the materials is predicted to be more stable during bending, with less risk of failure.

[0161] Further modifications of the invention within the scope of the claims would be apparent to a skilled person. In particular, the methodology of the invention allows the skilled person to investigate the properties of materials such as steel during bending. By comparison to pre-determined threshold values, the skilled person is able to evaluate the suitability of materials such as steel for a particular use using the method of the present invention.

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- US20080216585A [0012]

Non-patent literature cited in the description

- **Z. MARCINIAKJ.L DUNCANS.J. HU**Mechanics of Sheet Metal Forming, 0 7506 5300 [0007]
- **FLORANDO et al.**Journal of Mechanics and Physics of solids, 2005, vol. 53, 619-638 [0008]
- **L. GARDNER et al.**Journal of Constructional Steel Research, 2004, vol. 60, 1319-1332 [0009]
- **T. NAKAMURA et al.**Engineering Fracture Mechanics, 1986, vol. 25, 3323-339 [0010]
- **CHRISTOS CHAMIS**NASA Technical Note NASA TN D-7572, 1974, [0011]
- **T.X. YOUL.C. ZHANG**Plastic Bending- Theory and Application, 981022267X [0100]

Patentkrav

1. Fremgangsmåde til at karakterisere et metallisk materiale (10), der omfatter trinnene:

a. at tilvejebringe en plade af metallisk materiale (10) enkelt understøttet mellem to parallelle valse, idet nævnte valse har samme diameter;

b. at bøje pladen ved at tilvejebringe en ekstern kraft, F, via en bøjekniv, idet nævnte kraft fungerer i et plan vinkelret på planen dannet af valsenes midte, og som gennemskærer pladen ved midterlinjen mellem valsene, idet nævnte bøjekniv strækker sig mindst hele længden af pladen;

c. fremgangsmåde **kendetegnet ved at** den omfatter trinnene at beregne et tværsnitmoment, M, af det metalliske materiale ved at anvende følgendende ligning:

$$M = \frac{F \cdot L_m(\beta_1)}{2 \cdot cos^2(\beta_1)}$$

hvor

F er den anvendte bøjekraft,

L_m (β_1) er momentarmen ved vinkel β_1, beregnet ifølge følgende ligning:

$$L_m(\beta_1) = L_0 - (R_k + R_d) \cdot \sin(\beta_1)$$

hvor

L_0 er halvdelen af dyse-bredden,

R_d er radiussen af dyse-kanten,

R_k er radiussen af kniven, og

β_1 er bøjevinklen,

hvor bøjevinklen , β_1, er vinklen bevæget af the overfladenormalen af pladen ved kontaktpunktet med en af valsene under bøjning via den eksterne kraft, beregnet som 90° minus den akutte vinkel mellem de normalvektorer af starten og bøjede planer af pladen, idet startplanen svarer til planen dannet af midterlinjerne af de to parallelle valse, og det bøjede plan svarer til planen dannet af midterlinjen af en valse og kontaktlinjen mellem denne valse og pladen, hvis plan indeholder pladenormalen ved punktet, der er i kontakt med valsen.

2. Fremgangsmåde ifølge krav 1, hvor fremgangsmåden omfatter at løse energiligevægtsudtrykket:

$$\int F\, ds = \int 2M d\beta_2$$

hvor β_2 er den sande vinkel, hvortil pladen bøjes, beregnet som følger

$$\beta_2 = \beta_1 - \int \frac{t \cdot Sin(\beta_1)}{L_m(\beta_1)} \, d\beta_1$$

hvor t er tykkelsen af pladen.

3. Fremgangsmåde ifølge et hvilket som helst af de foregående krav, **kendetegnet ved at** den omfatter trinnene at beregne flydespændingen, σ_1 ved at anvende følgende ligning:

$$\sigma_1 = \frac{2}{B \cdot t^2 \cdot \varepsilon_1} \cdot \frac{d}{d\varepsilon_1}(M \cdot \varepsilon_1{}^2)$$

hvor hovedspændingen, ε_1 er beregnet fra:

$$\varepsilon_1 = \beta_2 \cdot \frac{t}{L_m(\beta_1)}$$

hvor B er prøvelængden, t er prøvetykkelsen og β_2 er den sande vinkel, som nævnte metalliske materiale (10) bøjes til under nævnte bøjetest.

4. Fremgangsmåde ifølge et hvilket som helst af de foregående krav, **kendetegnet ved at** den omfatter trinnene at estimere Youngs modul, E, af nævnte metalliske materiale (10) ved at tegne en graf af β_2 og nævnte beregnede tværsnitsmoment, M og at bestemme gradienten af den elastiske del af momentkurven, hvorved gradienten er

$$\left(\frac{2 \cdot E' \cdot I}{L_m}\right)$$

hvor I er momentet af inerti og hvor E er Youngs modul i almindeligt belastning og er givet af:

$$E' = \frac{E}{(1 - \nu^2)}$$

hvor ν er Poissons forhold.

5. Fremgangsmåde ifølge et hvilket som helst af de foregående krav, **kendetegnet ved at** det omfatter trinnet at anvende nævnte tværsnitsmoment, M af nævnte metalliske materiale for at estimere tilbagefjedring af nævnte metalliske materiale ved at anvende følgende ligninger:

$$\Delta\beta_{tot} = \beta_{C\,el} + \beta_{S\,el} + \Delta\beta_{12}$$

$$\beta_{C\,el} = \frac{M_L \cdot L_C}{E'I} = \frac{M_L \cdot \left(R_k + \frac{t}{2}\right) \cdot \beta_C}{2\,E'I}$$

$$\beta_{S\,el} = \frac{M_L \cdot L_S}{2\,E'I} = \frac{M_L}{2\,E'I} \cdot \frac{L_N}{\cos(\beta_1)}$$

$$\Delta\beta_{12} = \int \frac{t \cdot \sin\beta_1}{L_m} \mathrm{d}\beta_1$$

$$M_L = M \frac{L_m}{L_N}$$

idet den omtrentlige længde af flangen, der testes er:

$$\frac{L_N}{\cos(\beta_1)}$$

og længden af metallisk materiale i kontakt med kniven er:

$$\left(R_k + \frac{t}{2}\right) \cdot \beta_C$$

hvor: $\Delta\beta_{tot}$ er den samlede mængde af tilbagefjedring, β_{Sel} er tilbagefjedringen af flangen, β_{Cel} er tilbagefjedringen relateret til materialet i kontakt med kniven, M_L er det reducerede moment grundet knivens begrænsede krumning, L_N er momentarmen, L_S er længden af flangen, L_C er længden af materialet formet af kniven, R_k er knivens radius, og βC er kontaktvinklen mellem det metalliske materiale og kniven.

6. Fremgangsmåde ifølge et hvilket som helst af de foregående krav, **kendetegnet ved at** den omfatter trinnet at anvende nævnte tværsnitsmoment, M af nævnte metalliske materiale til at estimate en friktionskoefficient, μ, af nævnte metalliske materiale ved at anvende ligningen:

$$\mu = \left\| \frac{M - M_{mtrl}}{M_{mtrl}} \right\| \cdot \frac{1}{\tan\beta_1}$$

hvor M_{mtrl} er tværsnitsmomentet opnået ved at anvende friktionsfrit bøjetestudstyr.

7. Fremgangsmåde ifølge et hvilket som helst af de foregående krav, **kendetegnet ved at** nævnte beregnede tværsnitsmoment, M, eller den kalkulerede flydespænding, σ_1 eller det estimerede Youngs modul, E, anvendes til at optimere et produkt omfattende nævnte metalliske materiale (10).

8. Fremgangsmåde ifølge et hvilket som helst af de foregående krav, **kendetegnet ved at** nævnte metalliske materiale (10) er varmvalset metallisk materiale (10), såsom varmvalset stål.

9. Fremgangsmåde ifølge et hvilket som helst af kravene 1 til 7, **kendetegnet ved at** nævnte metalliske materiale (10) er et koldvalset metallisk materiale, såsom koldvalset stål.

10. Fremgangsmåde til at kendetegne et metalliske materiale (10) ifølge et hvilket som helst foregående krav, **kendetegnet ved at** den omfatter trinnene at udføre en bøjetest ifølge VDA 238-100-standarden.

11. Fremgangsmåde ifølge et hvilket som helst af de foregående krav, **kendetegnet ved at** fremgangsmåden omfatter at beregne forholdet M/M_e, defineret som:

$$\frac{M}{M_e} = \frac{3}{\left(\left(\frac{dM}{d\beta_2} \Big/ \frac{M}{\beta_2}\right) + 2\right)}$$

12. Fremgangsmåde ifølge krav 11, hvor forholdet M/M_e er beregnet for mindst to forskellige materialer, og egenskaberne af et komposit omfattende disse materialer er beregnet fra værdierne af de individuelle materialer.

13. Fremgangsmåde til at bestemme betingelserne under hvilke et materiale forbliver stabilt under bøjning, idet den nævnte fremgangsmåde omfatter fremgangsmåden ifølge krav 11 og yderligere **kendetegnet ved at** bestemme betingelserne under hvilke forholdet M/M_e forbliver under 1,5.

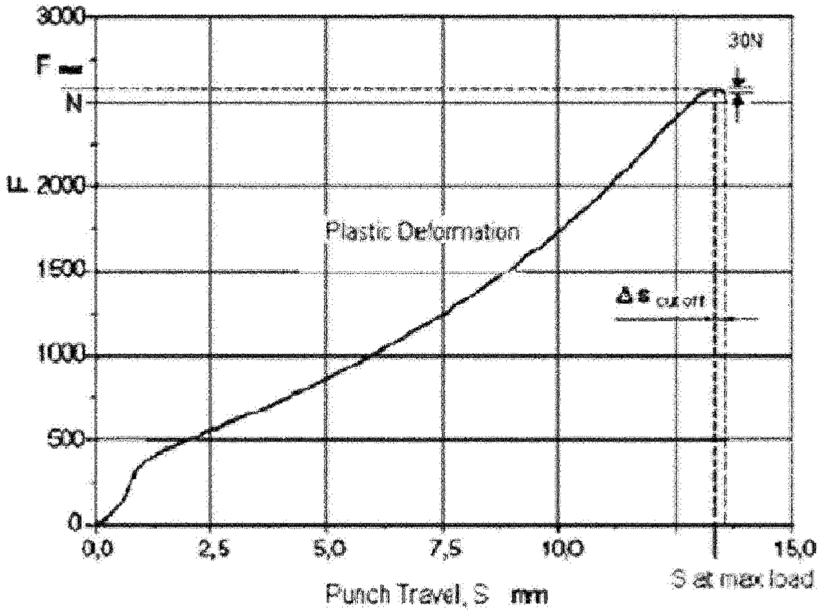
14. Fremgangsmåde ifølge et hvilket som helst af de foregående krav, hvor knivens radius, R_k, er mindre end eller lig med tykkelsen af det metalliske materiale, t.

15. Fremgangsmåde ifølge et hvilket som helst af de foregående krav, hvor knivens radius, R_k, er 0,7 gange tykkelsen af det metalliske materiale, t, eller mindre.

16. Computerprogramprodukt (30), **kendetegnet ved at** det omfatter et computerprogram omfattende computerprogramkodeorgan anbragt for at forårsage, at en computer eller en processor udfører beregningstrinnet ifølge en fremgangsmåde ifølge et hvilket som helst af de foregående krav, lagret på et computerlæsbart medium eller en bærebølge.

DRAWINGS

PRIOR ART



S in mm

Fig. 1

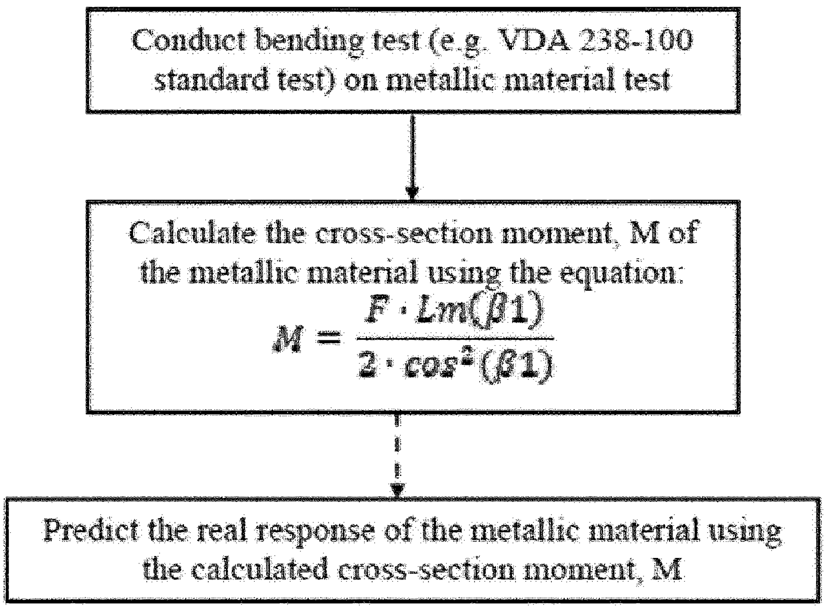
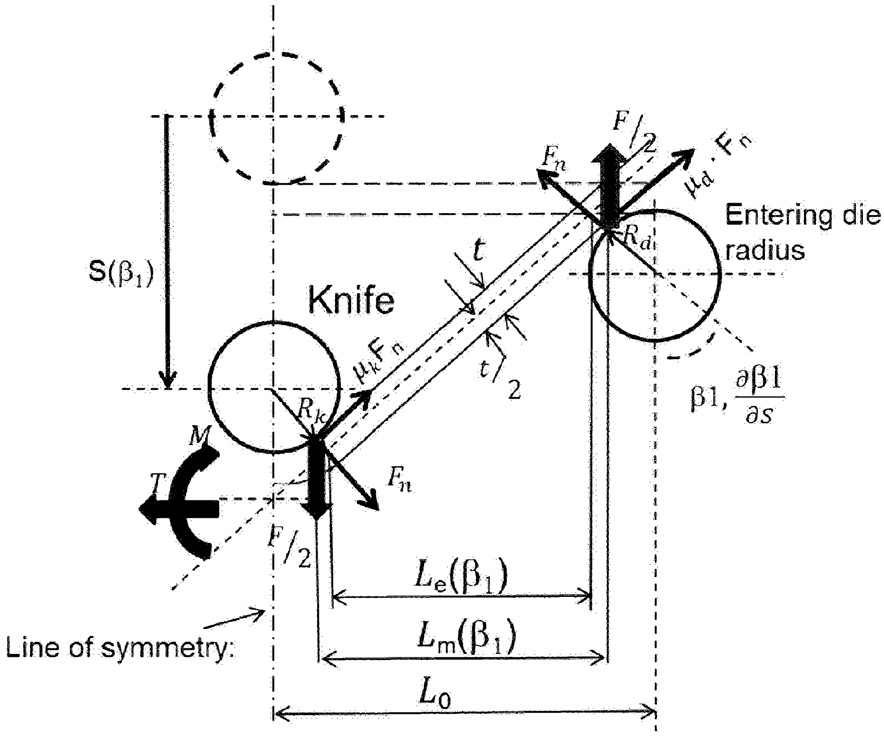
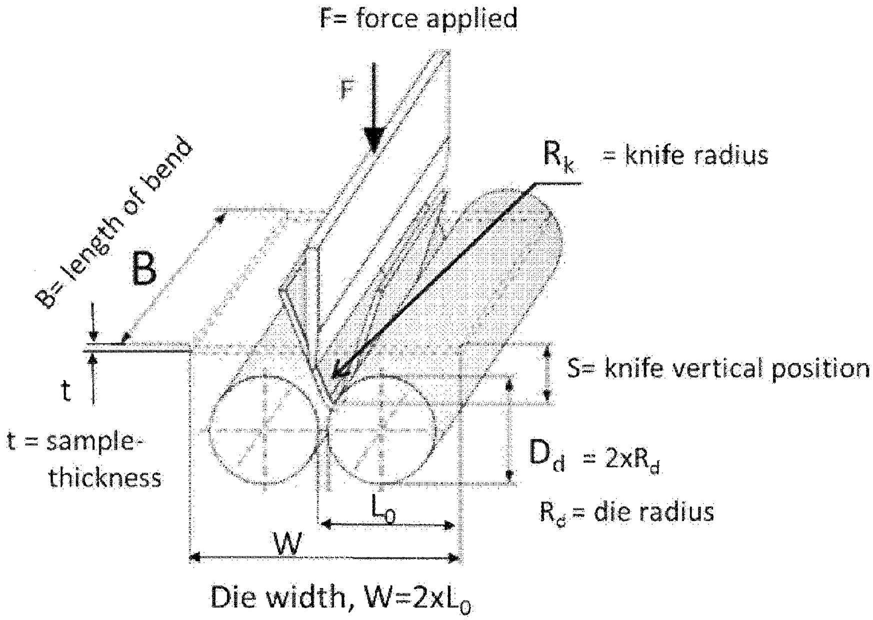


Fig. 2



S(β1)
Knife
t
t/2
F/2
Fn
μd · Fn
μk Fn
Rd
Rk
Entering die radius
β1, ∂β1/∂s
M
T
Le(β1)
Lm(β1)
L0
Line of symmetry:

Fig. 3a



F= force applied
F
Rk = knife radius
B= length of bend
B
t
t = sample-thickness
S= knife vertical position
Dd = 2xRd
Rd = die radius
L0
W
Die width, W=2xL0

Fig. 3b

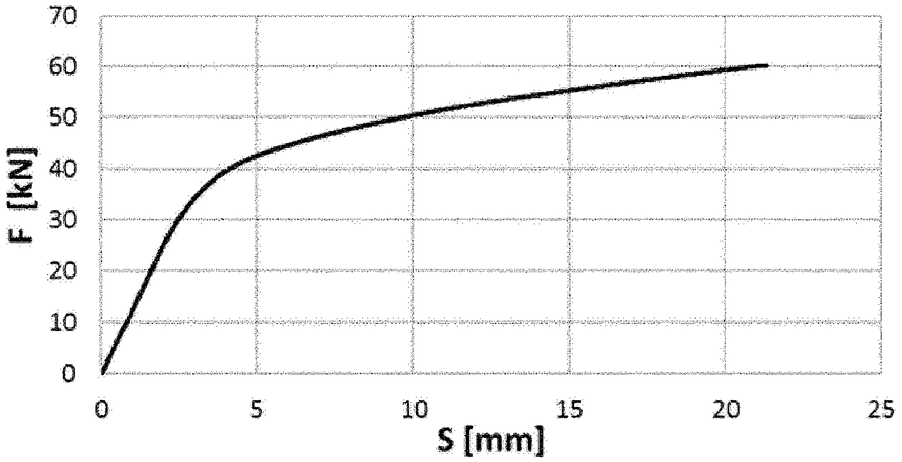


Fig. 4

PRIOR ART

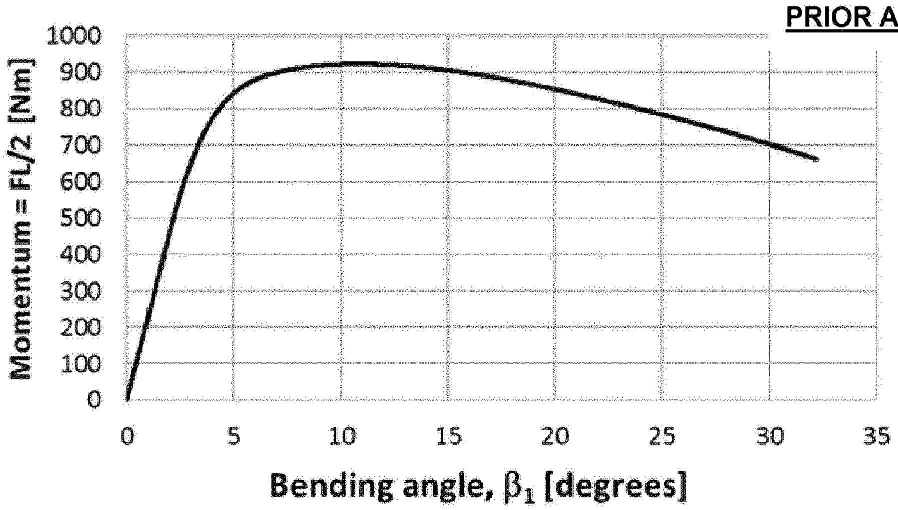
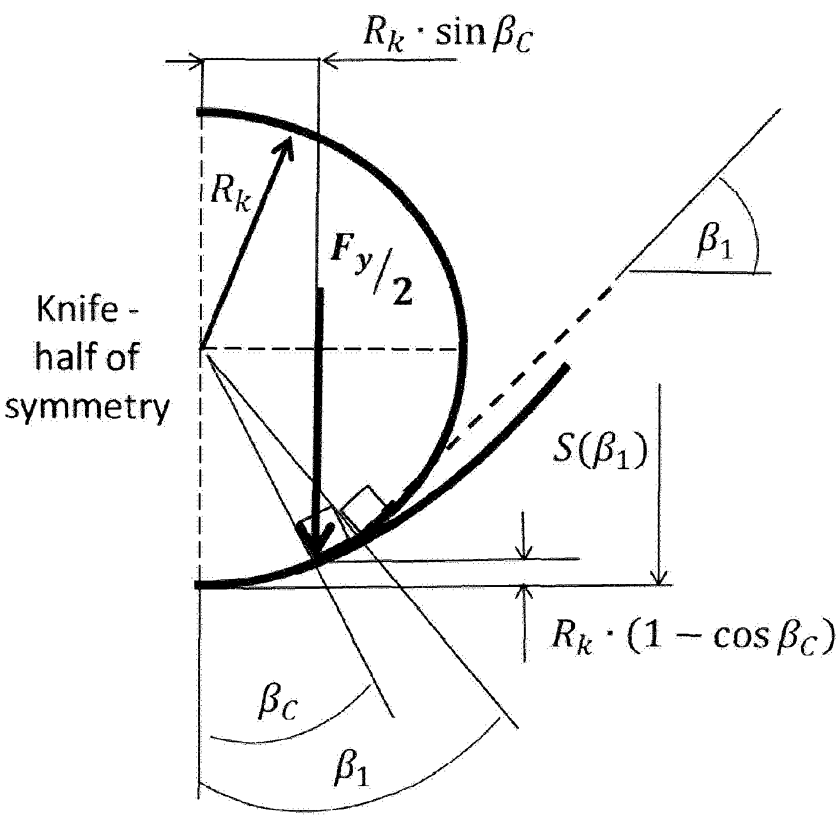
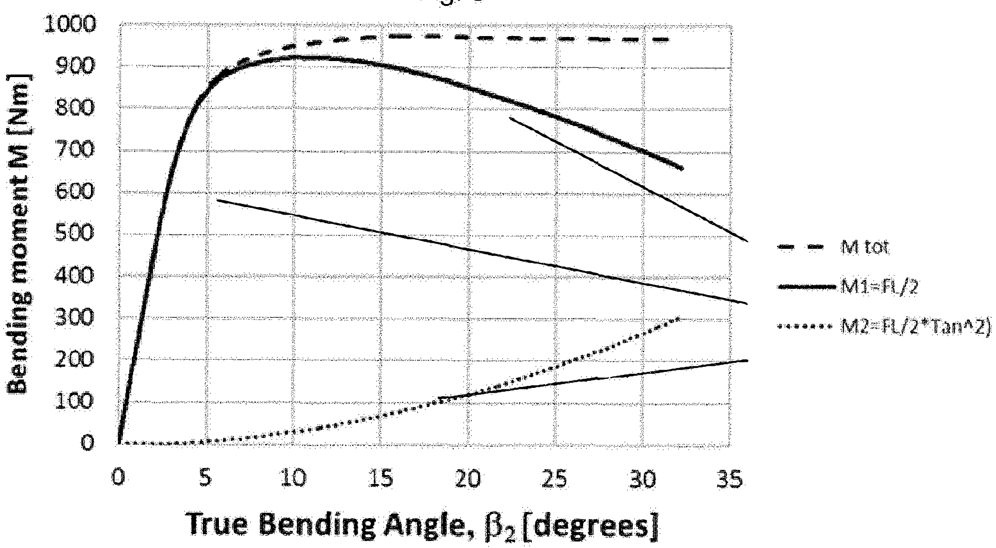


Fig. 5



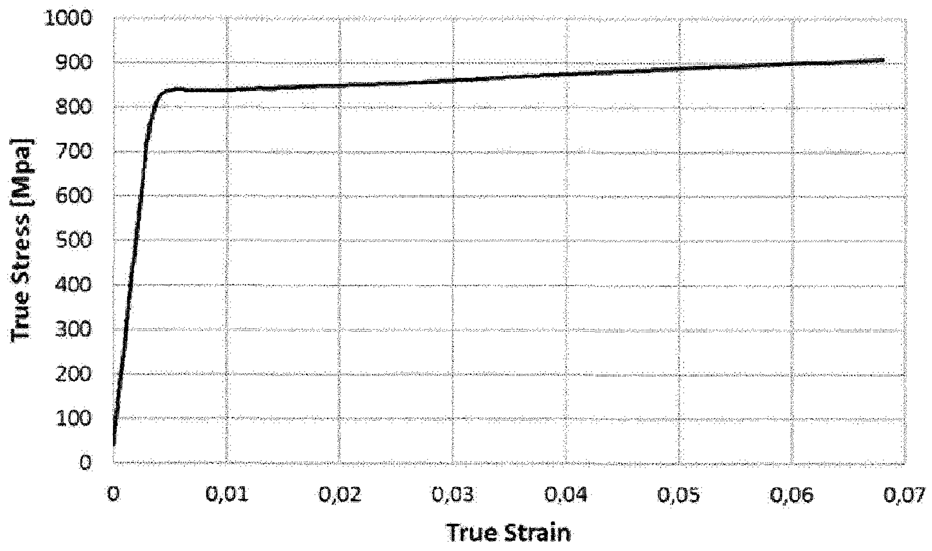
$R_k \cdot \sin\beta_C$
R_k
$F_y/2$
Knife - half of symmetry
β_1
$S(\beta_1)$
$R_k \cdot (1 - \cos\beta_C)$
β_C
β_1

Fig. 6



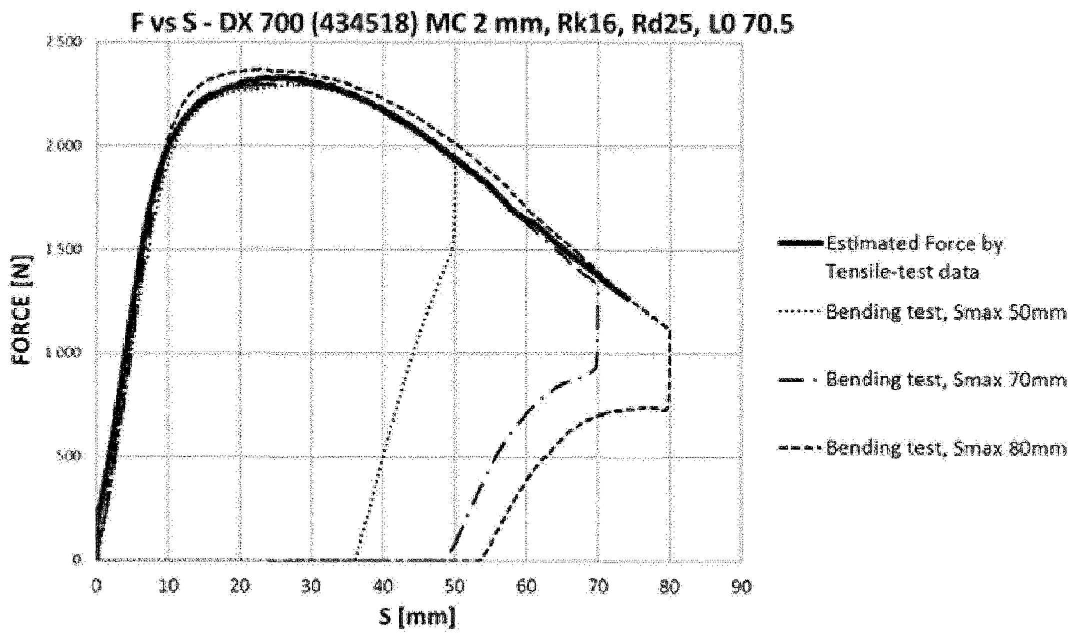
Bending moment M [Nm]
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
True Bending Angle, β2 [degrees]
M tot
M1=FL/2
M2=FL/2*Tan^2)

Fig. 7



True Stress [Mpa]
1000
900
800
700
600
500
400
300
200
100
0
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
True Strain

Fig. 8



F vs S - DX 700 (434518) MC 2 mm, Rk16, Rd25, L0 70.5
FORCE [N]
2 500
2 000
1 500
1 000
500
0
0
10
20
30
40
50
60
70
80
90
S [mm]
Estimated Force by Tensile-test data
Bending test, Smax 50mm
Bending test, Smax 70mm
Bending test, Smax 80mm

Fig. 9

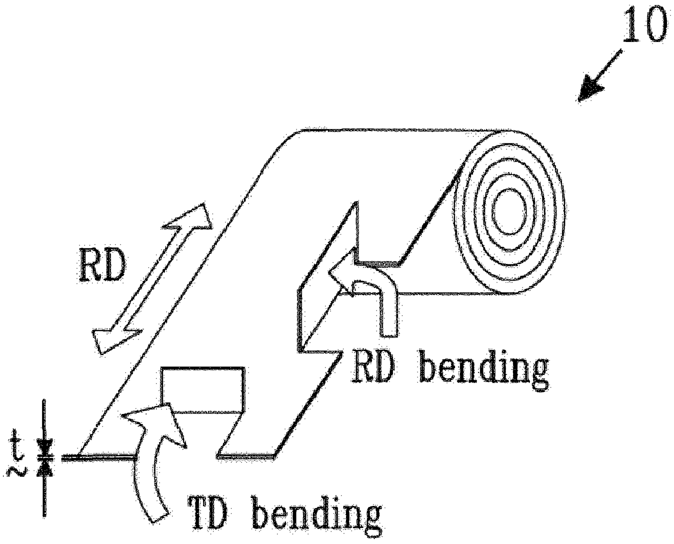


Fig. 10

$$M_e = \frac{B \cdot t^2 \cdot \sigma_1}{6}$$

$$M_{max} = \frac{B \cdot t^2 \cdot \sigma_1}{4}$$

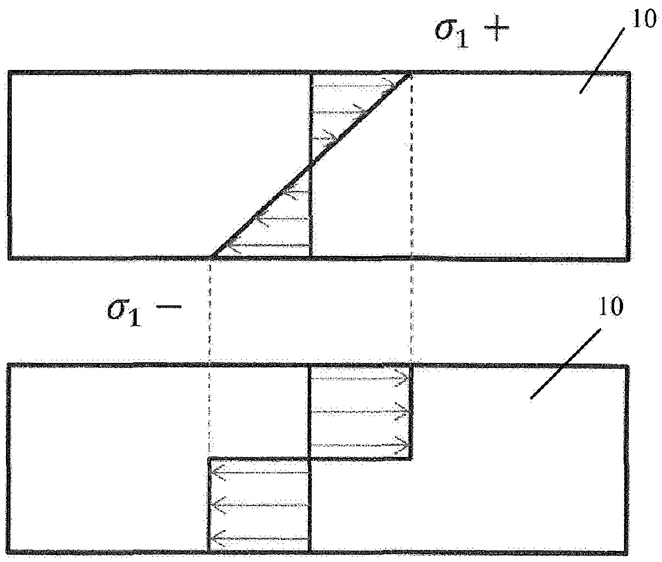


Fig. 11

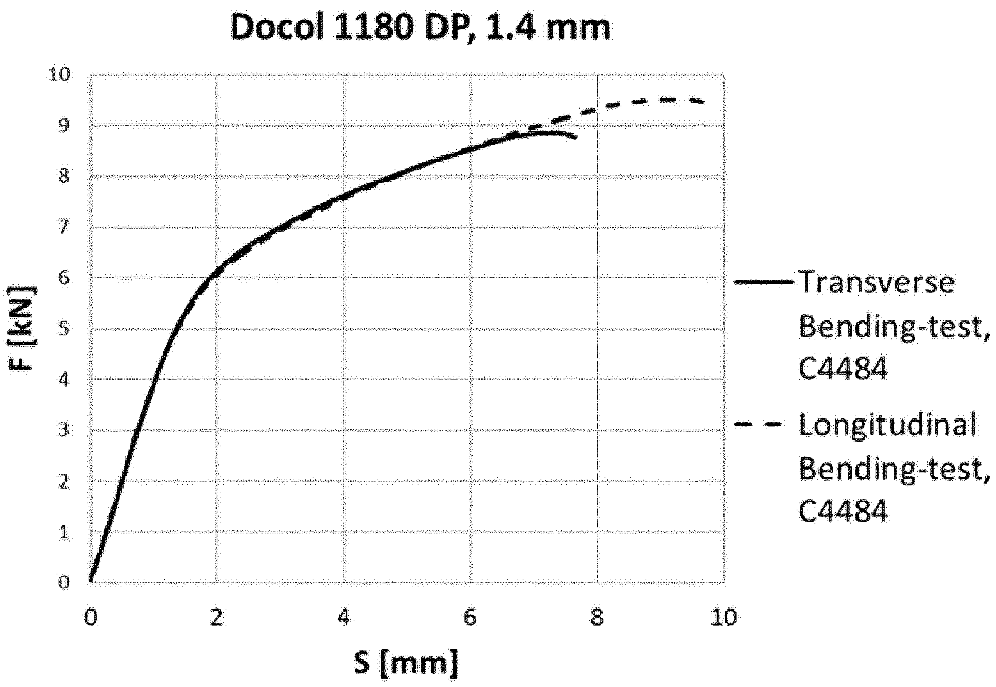

Docol 1180 DP, 1.4 mm
F [kN]
S [mm]
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
Transverse Bending-test, C4484
Longitudinal Bending-test, C4484

Fig. 12

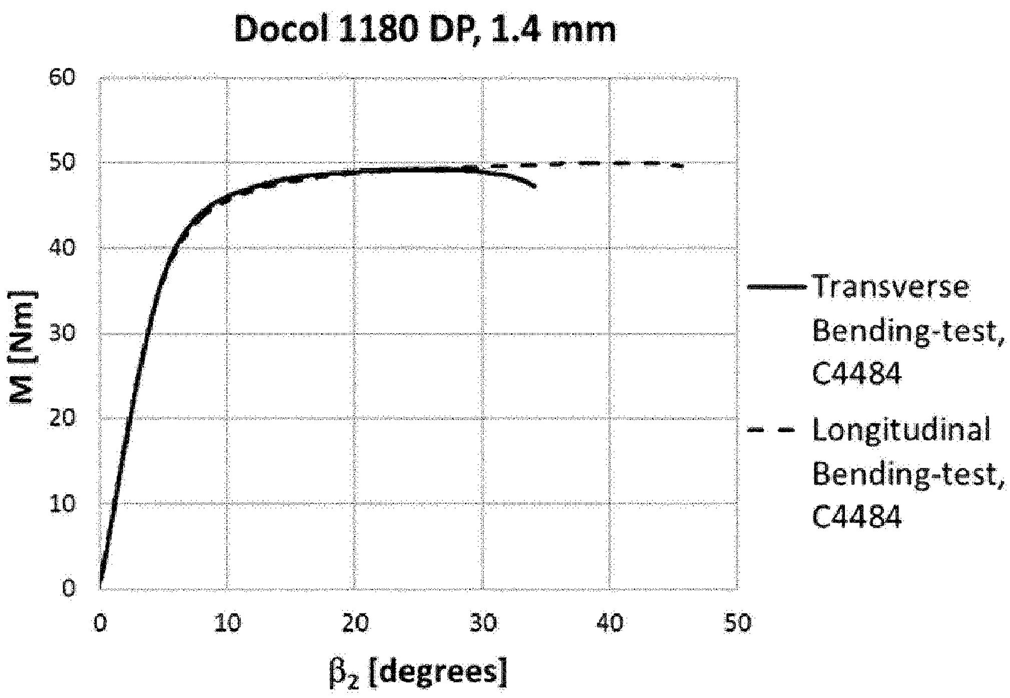

Docol 1180 DP, 1.4 mm
M [Nm]
β_2 [degrees]
0
10
20
30
40
50
60
0
10
20
30
40
50
Transverse Bending-test, C4484
Longitudinal Bending-test, C4484

Fig. 13

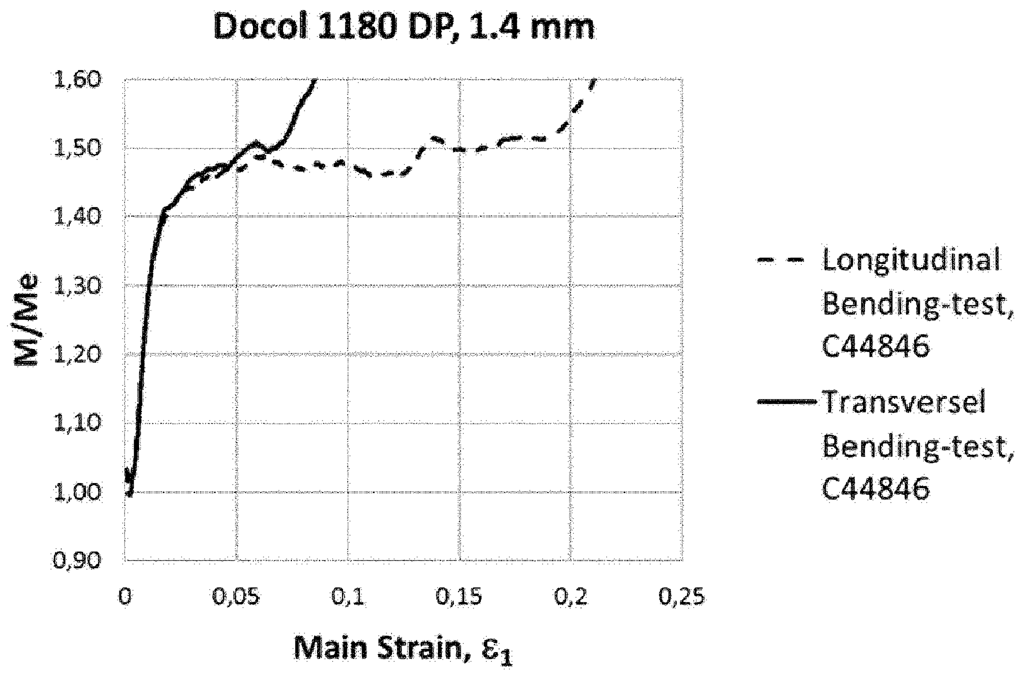

Docol 1180 DP, 1.4 mm
1,60
1,50
1,40
1,30
1,20
1,10
1,00
0,90
M/Me
0
0,05
0,1
0,15
0,2
0,25
Main Strain, ε_1
Longitudinal Bending-test, C44846
Transversel Bending-test, C44846

Fig. 14

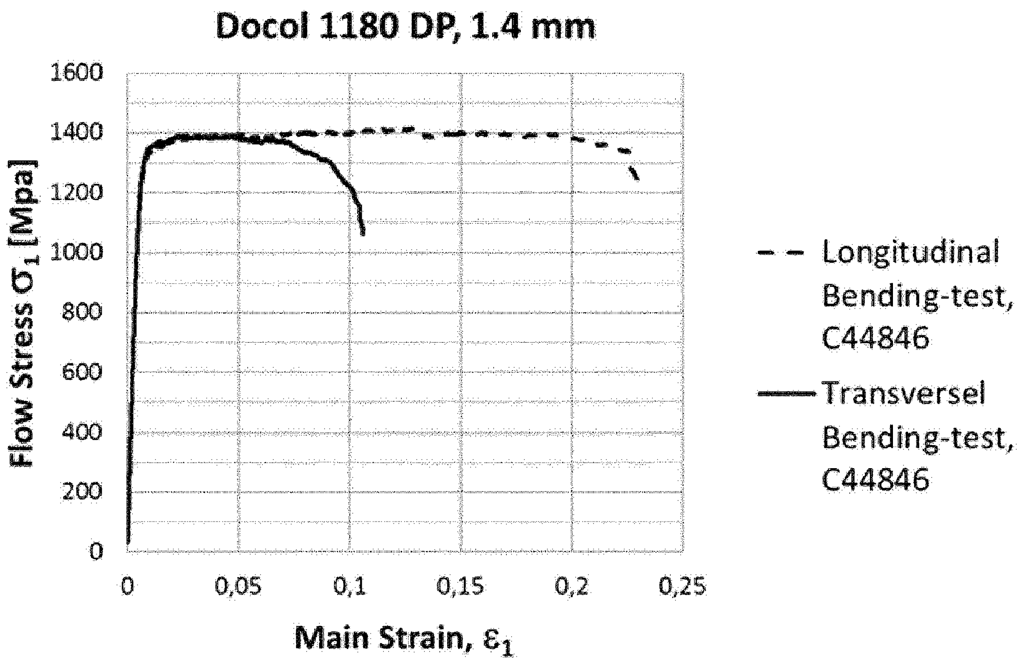

Docol 1180 DP, 1.4 mm
1600
1400
1200
1000
800
600
400
200
0
Flow Stress σ_1 [Mpa]
0
0,05
0,1
0,15
0,2
0,25
Main Strain, ε_1
Longitudinal Bending-test, C44846
Transversel Bending-test, C44846

Fig. 15

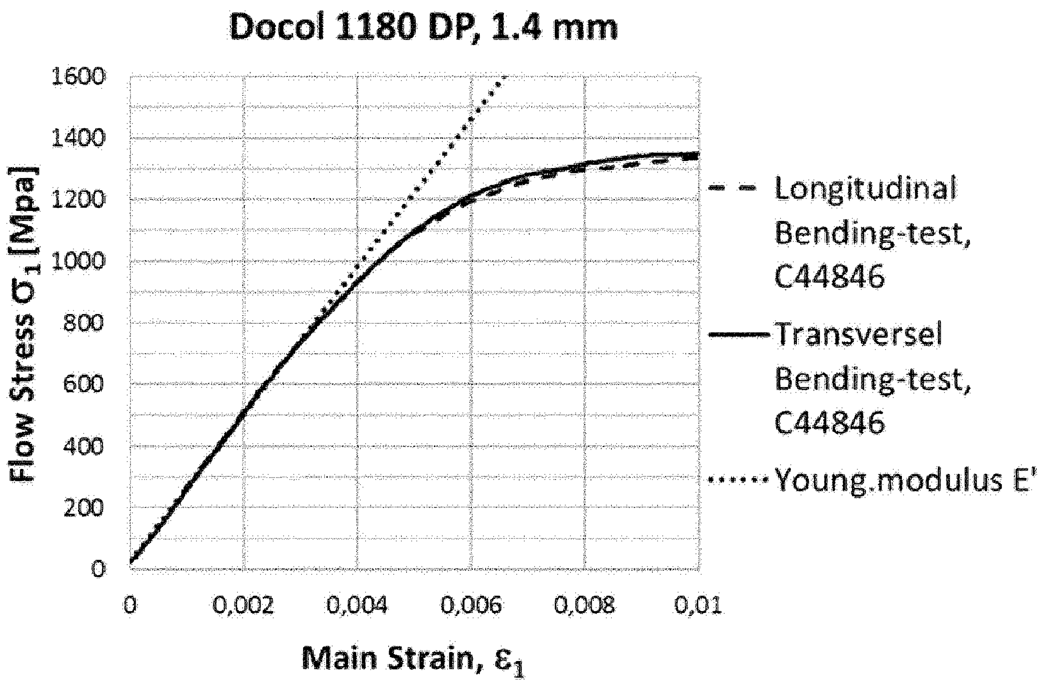

Docol 1180 DP, 1.4 mm
Flow Stress σ1 [Mpa]
1600
1400
1200
1000
800
600
400
200
0
0
0,002
0,004
0,006
0,008
0,01
Main Strain, ε1
Longitudinal Bending-test, C44846
Transversel Bending-test, C44846
Young.modulus E'

Fig. 16

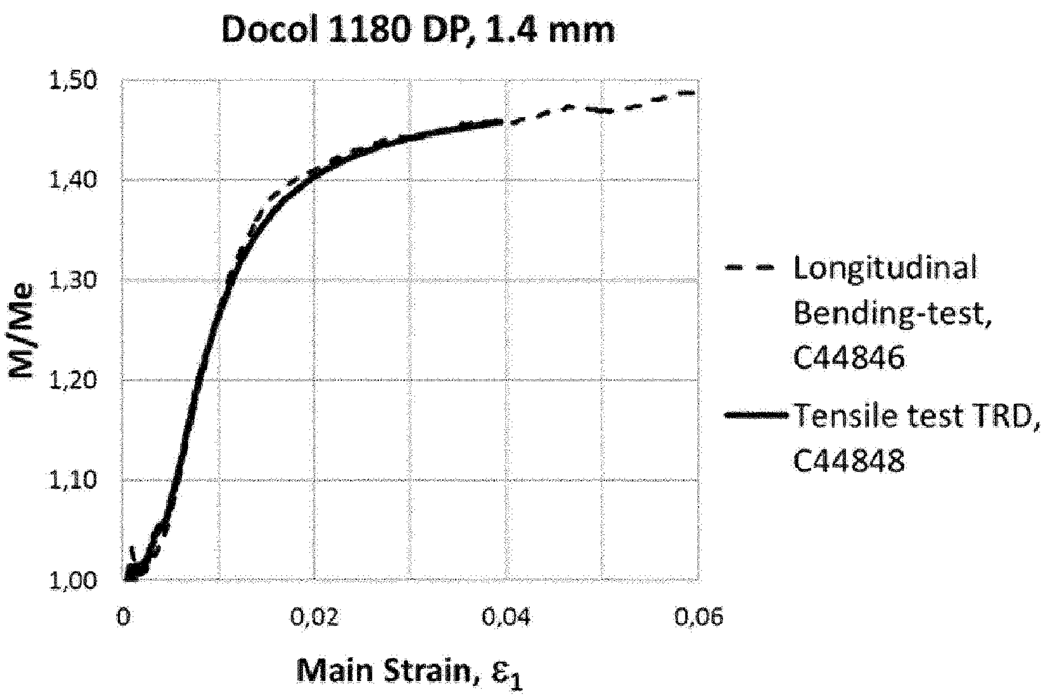

Docol 1180 DP, 1.4 mm
M/Me
1,50
1,40
1,30
1,20
1,10
1,00
0
0,02
0,04
0,06
Main Strain, ε1
Longitudinal Bending-test, C44846
Tensile test TRD, C44848

Fig. 17

<u>Reference test, i.e. get "thumb-print" of the material.</u>
Conduct VDA 238-100 standard test or another type of friction free bending, with small knife in relation to thickness and with a narrow die width.

Calkulating the Moment curve, $M_1\ (\varepsilon_2)$, from reference-test.

Making a geometrical transformation in line with the case to be analyzed: $\varepsilon_{22} = \varepsilon_2 \cdot \frac{t_2}{t_1}$, $M_2 = M_1 \cdot \left(\frac{t_2}{t_1}\right)^2 \cdot \frac{B_2}{B_1}$

Calculate bending angle by: $\beta_{22} = \frac{\varepsilon_{22} \cdot L_m}{t_2}$

Calculate the contact angle β_C and then the real moment-arm L_N

Using the invented expression $M_L = M_2 \frac{L_m}{L_N}$

Estimate the springback based on reduced moment M_L and contact angle β_C

Fig. 18

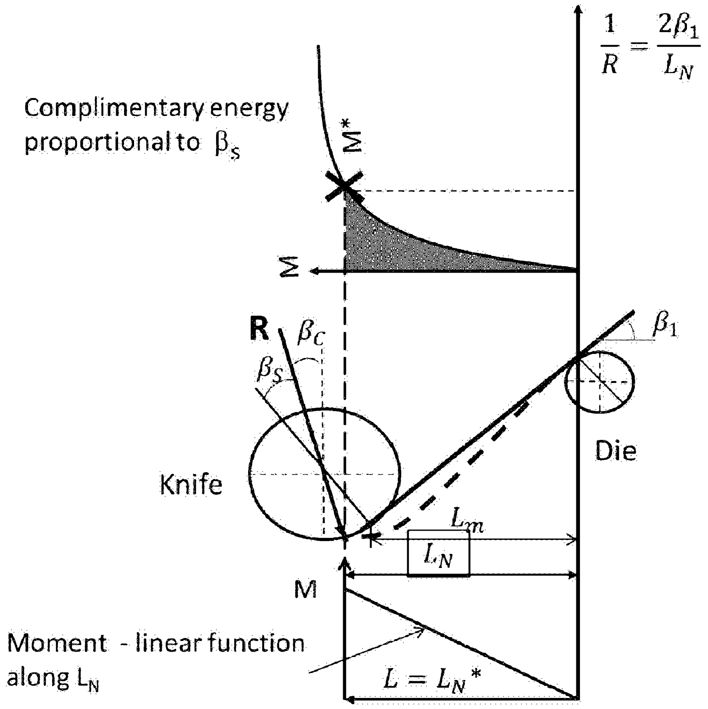


Fig. 19

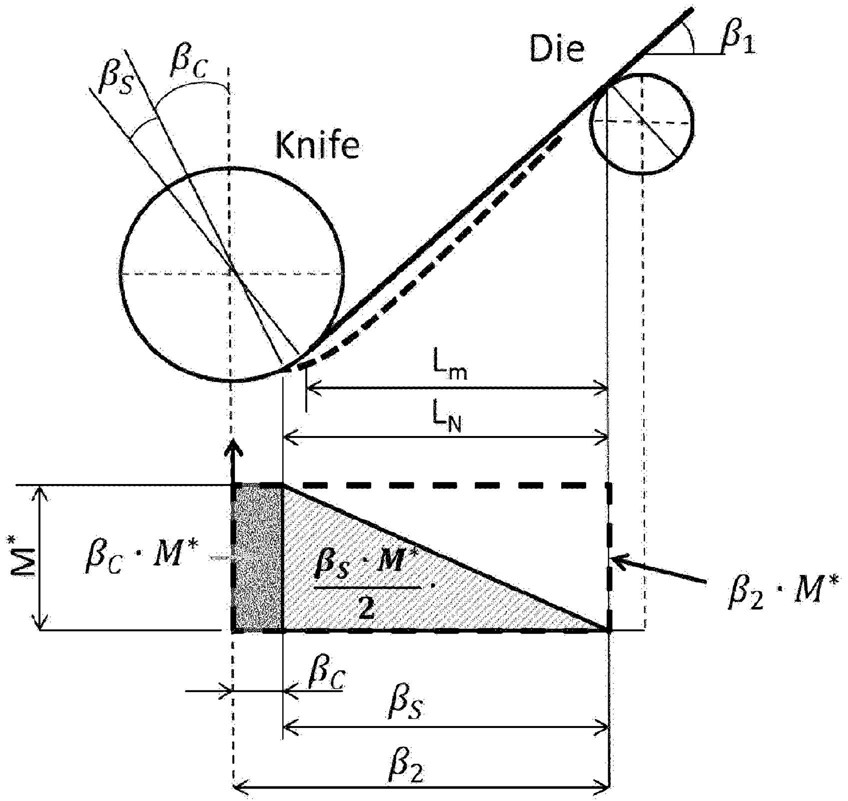

β_S
β_C
Die
β_1
Knife
L_m
L_N
M^*
$\beta_C \cdot M^*$
$\frac{\beta_S \cdot M^*}{2}$
$\beta_2 \cdot M^*$
β_C
β_S
β_2

Fig 20

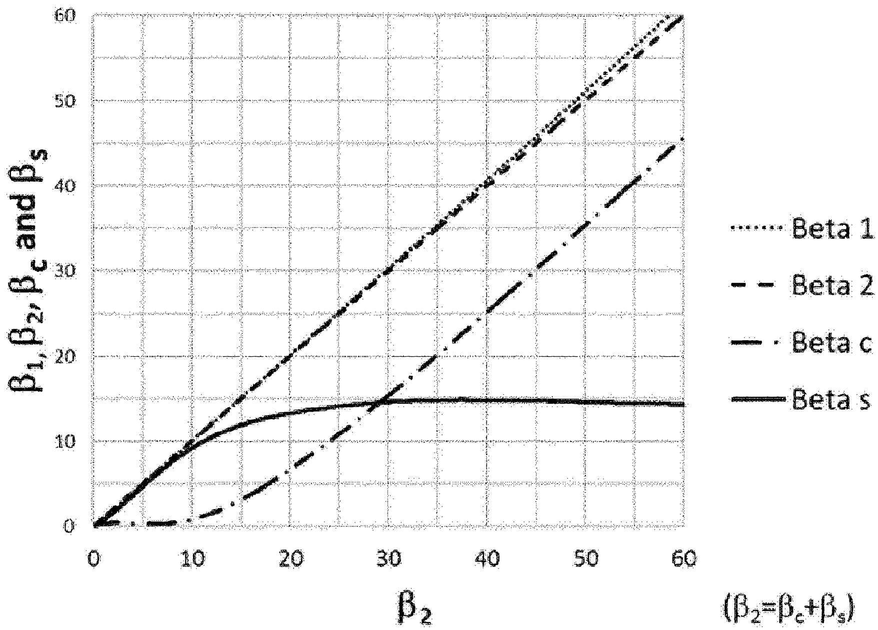
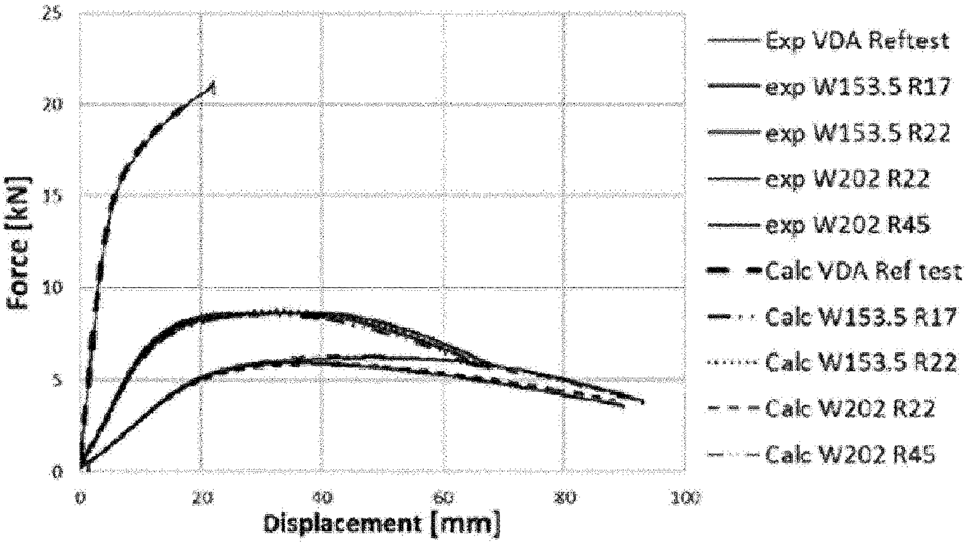
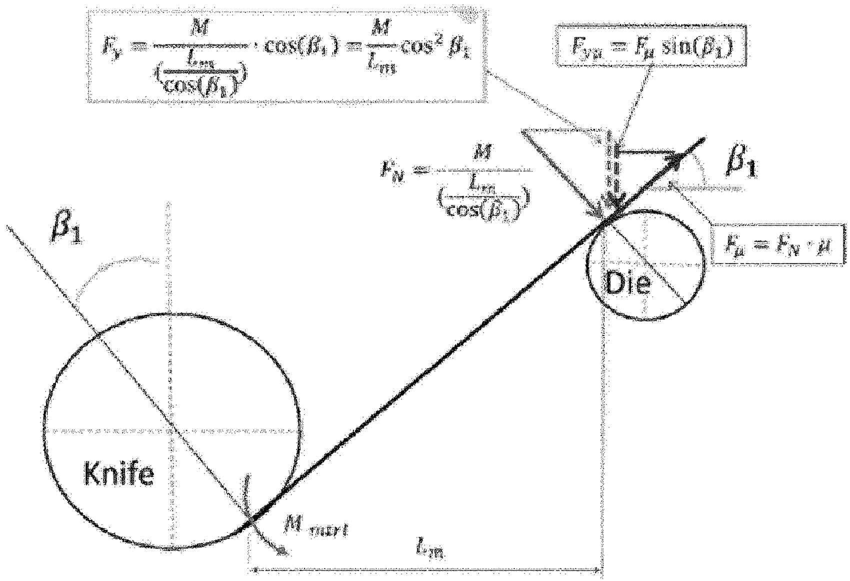

$\beta_1, \beta_2, \beta_c$ and β_s
0
10
20
30
40
50
60
Beta 1
Beta 2
Beta c
Beta s
β_2
$(\beta_2=\beta_c+\beta_s)$

Fig. 21



Force [kN]
Displacement [mm]
Exp VDA Reftest
exp W153.5 R17
exp W153.5 R22
exp W202 R22
exp W202 R45
Calc VDA Ref test
Calc W153.5 R17
Calc W153.5 R22
Calc W202 R22
Calc W202 R45

Fig. 22



$F_y = \frac{M}{(\frac{L_m}{\cos(\beta_1)})} \cdot \cos(\beta_1) = \frac{M}{L_m} \cos^2 \beta_1$
$F_{y\mu} = F_\mu \sin(\beta_1)$
$F_N = \frac{M}{(\frac{L_m}{\cos(\beta_1)})}$
β_1
$F_\mu = F_N \cdot \mu$
Die
β_1
Knife
M_{matrl}
L_m

Fig. 23

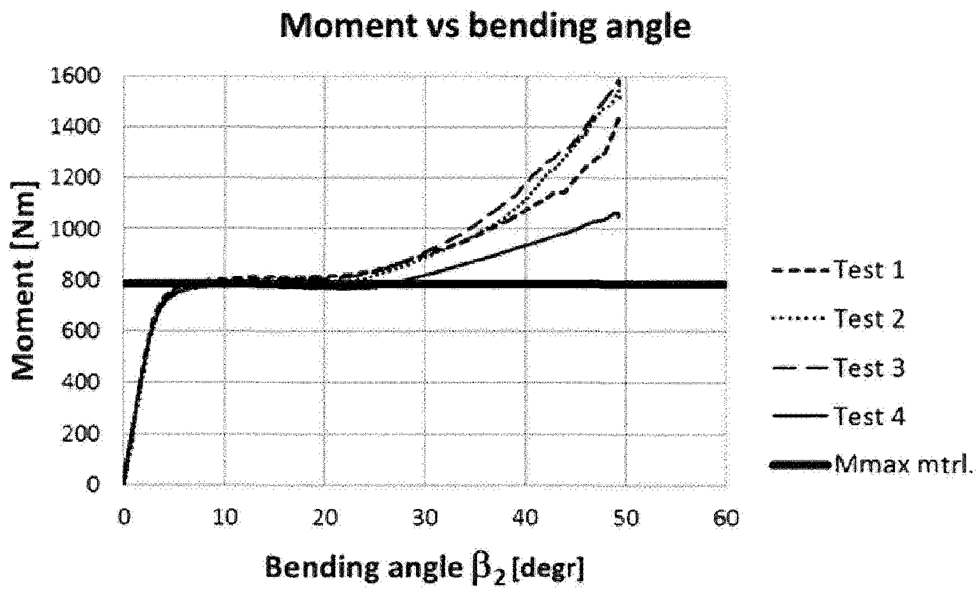

Moment vs bending angle
1600
1400
1200
1000
800
600
400
200
0
Moment [Nm]
0
10
20
30
40
50
60
Bending angle β2 [degr]
Test 1
Test 2
Test 3
Test 4
Mmax mtrl.

Fig. 24

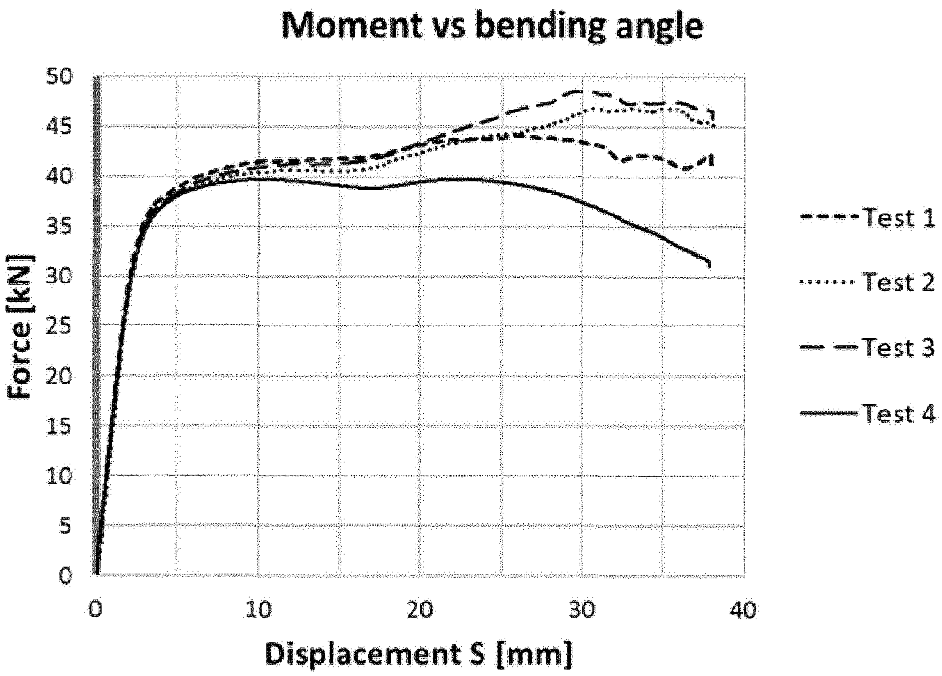

Moment vs bending angle
50
45
40
35
30
25
20
15
10
5
0
Force [kN]
0
10
20
30
40
Displacement S [mm]
Test 1
Test 2
Test 3
Test 4

Fig. 25

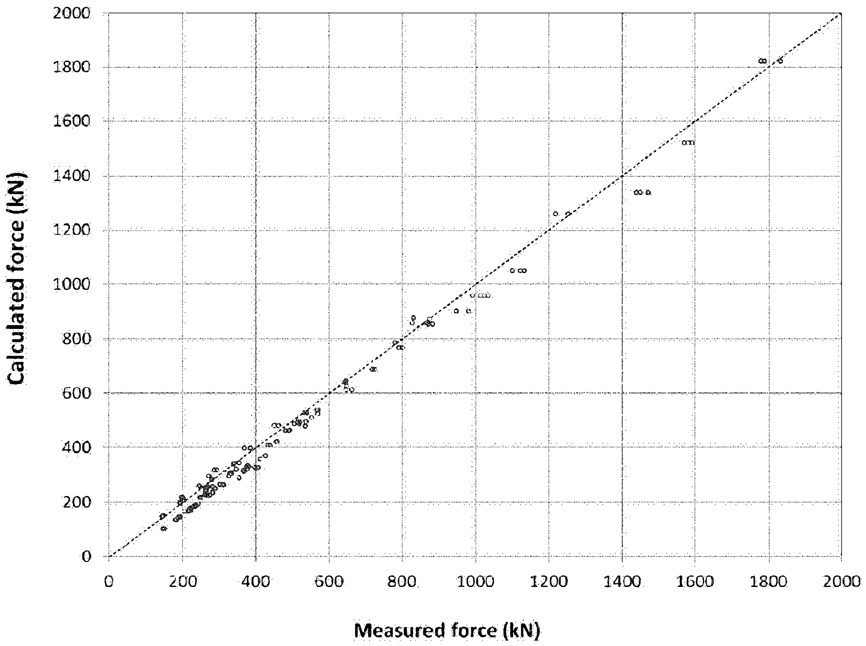

2000
1800
1600
1400
1200
1000
800
600
400
200
0
Calculated force (kN)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Measured force (kN)

Fig. 26

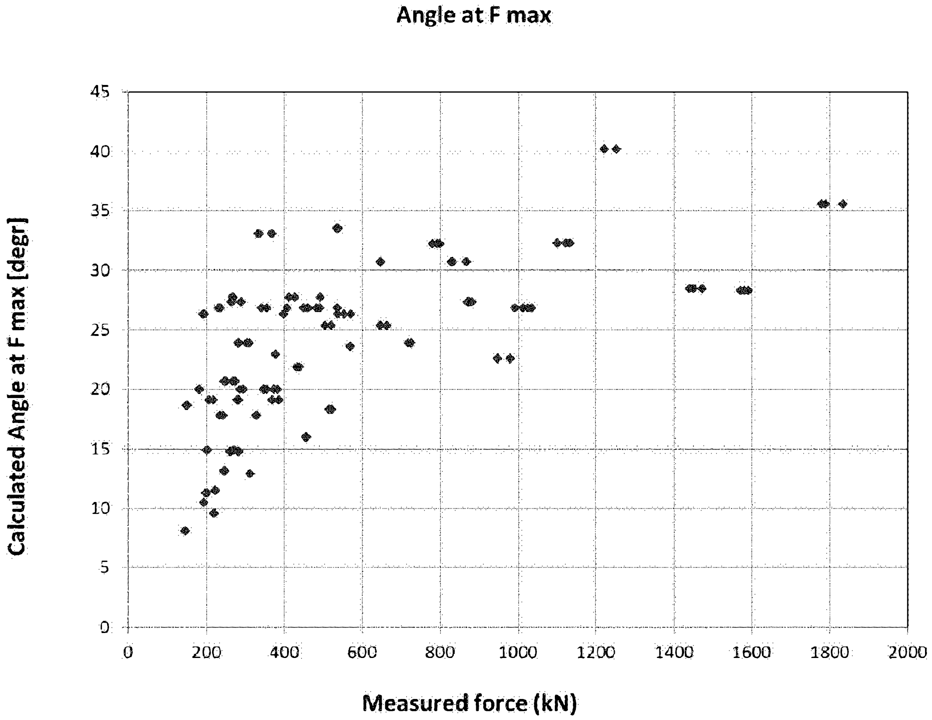

Angle at F max
45
40
35
30
25
20
15
10
5
0
Calculated Angle at F max [degr]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Measured force (kN)

Fig. 27

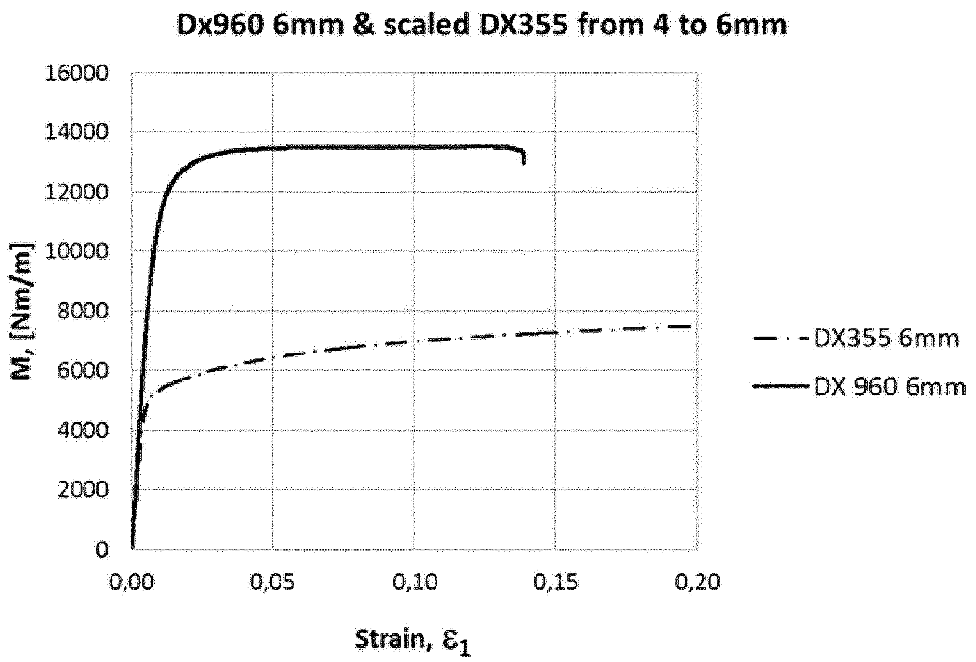

Dx960 6mm & scaled DX355 from 4 to 6mm
16000
14000
12000
10000
8000
6000
4000
2000
0
M, [Nm/m]
0,00
0,05
0,10
0,15
0,20
Strain, ε1
DX355 6mm
DX 960 6mm

Fig. 28

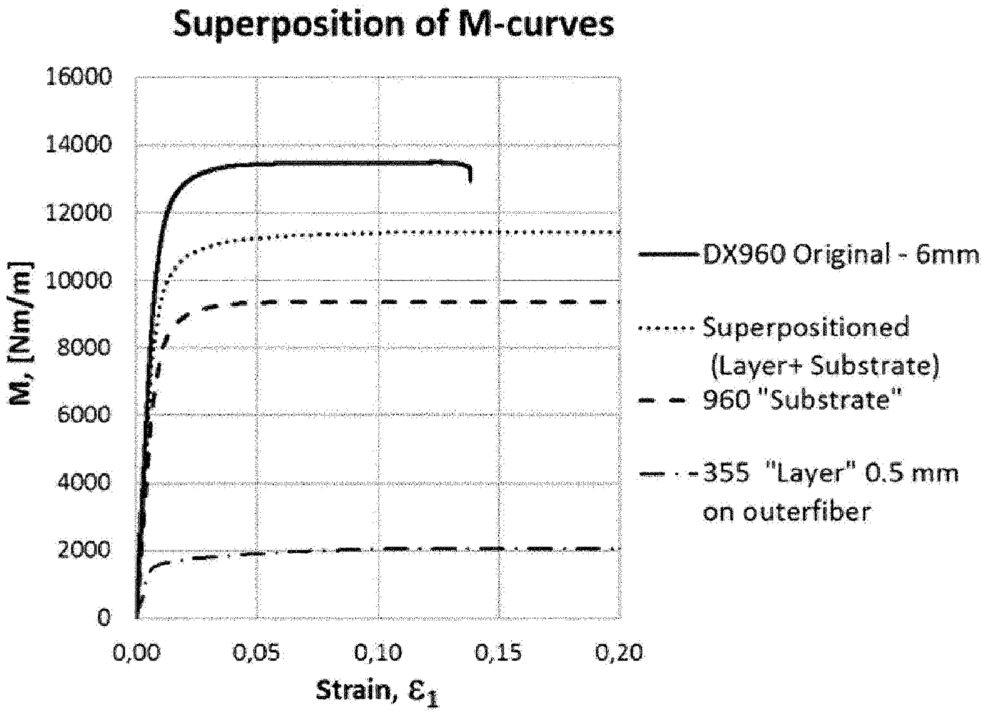

Superposition of M-curves
16000
14000
12000
10000
8000
6000
4000
2000
0
M, [Nm/m]
0,00
0,05
0,10
0,15
0,20
Strain, ε1
DX960 Original - 6mm
Superpositioned (Layer+ Substrate)
960 "Substrate"
355 "Layer" 0.5 mm on outerfiber

Fig. 29

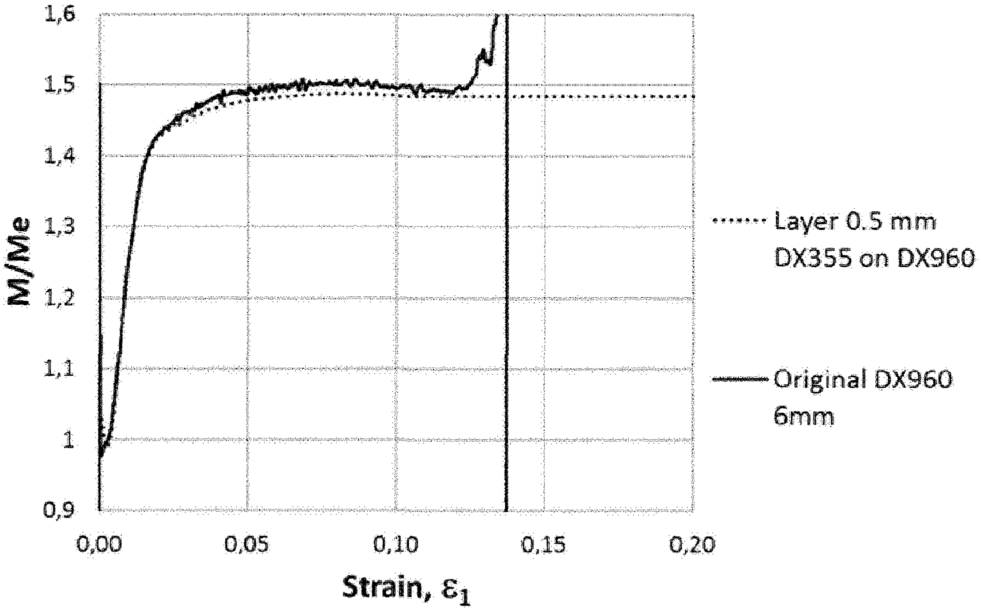

1,6
1,5
1,4
1,3
1,2
1,1
1
0,9
M/Me
0,00
0,05
0,10
0,15
0,20
Strain, ε_1
Layer 0.5 mm
DX355 on DX960
Original DX960
6mm

Fig. 30