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5.3.6. — wzmocnienie
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On experimental studies of yield surfaces of metals; a more general approach

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Abstract

In all existing experimental studies of the effect of plastic deformation on yield condition the results of tests are represented by assuming a certain standard coordinate system. When thin-walled tubular specimens are used the coordinate axes x,y are assumed to coincide with the axial and circumferential directions on the tube. When specimens are cut out from a prestressed metal sheet the coordinate axes are so chosen that they are parallel to the edges of the sheet.

It is shown in the present study that the interpretation of experimental results may be more instructive if for the same test variously oriented coordinate systems x,y are used. Numerous experimental results are recalculated for variously oriented coordinate systems and then represented in the respective stress space corresponding to the assumed orientation of the reference axes.

Such various representations of the deformation-induced changes of the yield surface will constitute the experimental basis for a more sound analysis of the theory of deformation-induced anisotropy of metals. If the plastic properties of the tested material in its initial state are isotropic we can always choose arbitrarily a reference system in which the deformation-induced anisotropy will later be described.

1 Introduction

Over sixty years elapsed since Lode [1] published his classical paper reporting experimental investigations of yield surfaces of some metals in virgin state. For almost thirty years since then no paper reporting experimental tests of this kind has been published, except that by Taylor and Quinney [2], who used thin-walled tubular specimens made of various metals. The concept of this work was different than that in the Lode's investigations, becouse each specimen was prestrained by axial stresses beyond the initial yield locus and then after partial unloading was additionally loaded by increasing twisting moment while the axial stress was kept constant. The conventional yield locii have been found by extrapolating the smooth portion of the stress-strain diagram back to intersect the extrapolated straight initial portion of the diagram. This was a quite different approach than that used in most recent papers in wchich the proportional limit during subsequent loading was taken as a conventional yield stress.

Experimental investigations of surfaces of prestrained metals began to attract the attention of numerous scientists in the late fifties when the strain -hardening phenomenon under complex loadings became one of the most important problems in the development of the theory of plasticity. Numerous experimental works in this field have been described in two survey papers by Ikegami [3,4]. Thus they will not be mentioned here.

The aim of this paper is to present a more general look at a interpretation of the results of experimental studies of yield surfaces of plastically deformed metals. Our considerations will be based on the fact that most metals in virgin state display isotropic plastic properties. Thus the analysis presented below is valid for initially isotropic materials only.

2 The theory of experiments on plastic yielding under plane stress conditions

At first we shall present in brief the foundations of experiments concerning the behaviour of yield surfaces of metals undergoing complex plastic deformations (cf.[5]). Such experiments are usually performed under plane stress conditions. Mostly thin-walled tubular specimens are used. They are loaded simultaneously by various combinations of axial force, a twisting moment and internal pressure. At a definite point of an arbitrarily choosen Cartesian co-ordinate system x,y with the x,y -plane coinciding with the local tangent plane to the specimen's surface, there exist three stress components σ_x, σ_y, τ_{xy} only, the stress component σ_z perpendicular to this surface beeing equal to zero or beeing so small that it may be neglected in the analysis. It is important to emphasize that axes x and y can be chosen arbitrarily. They not necessarily must coincide with the axial and circumferential directions on the surface of a tubular specimen.

The Huber-Mises yield condition for isotropic materials under plane stress conditions assumes the form

$$\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 + 3\tau_{xy}^2 = 3k^2 \tag{1}$$

where k is the yield stress under pure shear conditions. In the stress space of non-vanishing components σ_x, σ_y, τ_{xy} yield condition (1) is represented by the points of the surface of an ellipsoid shown in Fig.1. One of its principal axes coincide with the τ_{xy} -axis and other two lie in the $\sigma_x\sigma_y$ -plane. They bisect the right angles made by reference axes σ_x and σ_y. By heavy lines are shown in the figure certain particular ellipses on the surface of the ellipsoid. They correspond to the loading modes most

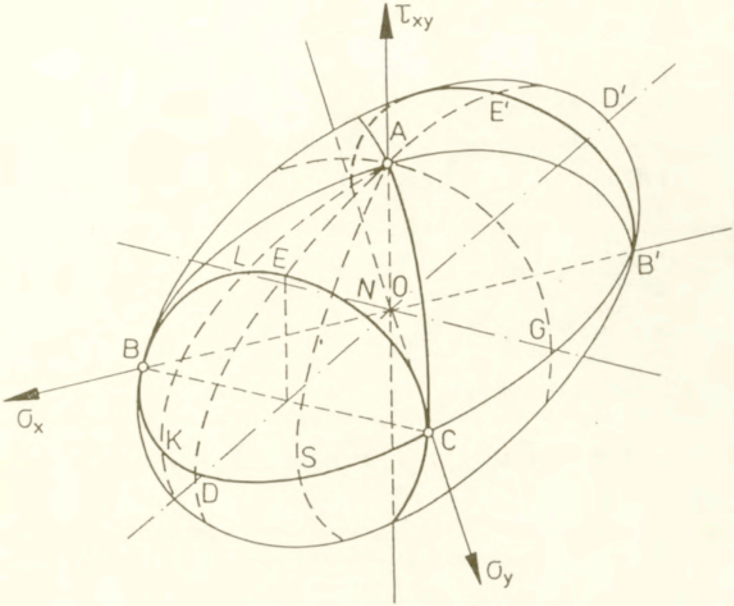


Figure 1:

commonly used in testing yield surfaces with the use of tubular specimens. For instance, ellipse AB for which $\sigma_y = 0$ corresponds to simultaneous torsion and axial tension of the specimen, if x is chosen as the axial direction. Portion BCD of the ellipse lying in the $\sigma_x \sigma_y$ -plane corresponds to the simultaneous loading of the tubular specimen by the axial force and by internal pressure.

The paths of proportional loadings are represented in the stress space by straight lines originating from the central point O. For instance, if the x and y -directions coincide with the directions of principal stresses, the path of proportional loading with constant ratio of principal stresses will be represented by a straight line lying in the plane σ_x, σ_y, such as line OP in Fig.2. Let us consider an arbitrary stress state represented by the point P on the line OP. Stress components written in the system of coordinate axes x,y arbitrarily inclined with respect to the directions of principal stresses σ_1, σ_2 satisfy the known relations

$$\begin{aligned} (\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2 &= (\sigma_1 - \sigma_2)^2 \\ \sigma_x + \sigma_y &= \sigma_1 + \sigma_2 \end{aligned} \tag{2}$$

These equations represent a certain ellipse lying in the plane perpendicular to the

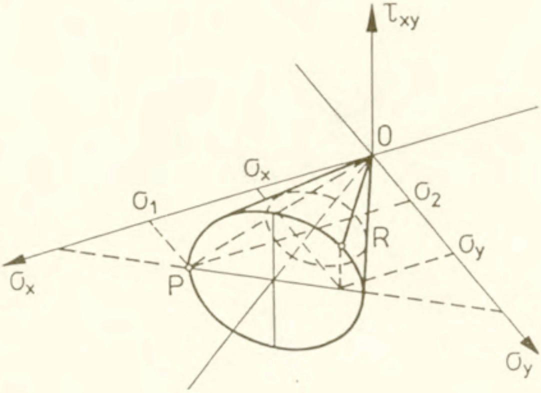


Figure 2:

bisector of the right angle between the axes σ_x and σ_y (Fig.2). All the points on this ellipse represent the same stress state written in various reference frames. Similarly each straight line connecting the origin O with an arbitrary point R on the ellipse corresponds to the proportional loading path OP, referred to the different coordinate system. Representations of the same proportional loading path (say OP) in various rotated coordinate systems generate the surface of an elliptical cone. Its equation is

$$\kappa(\sigma_x^2+\sigma_y^2)-(1+\kappa^2)\sigma_x\sigma_y+(1+\kappa)^2\tau_{xy}^2=0 \tag{3}$$

Here $\kappa=\sigma_1/\sigma_2$ is a parameter characterizing the proportional loading path.

Intersections of cones (3) with the yield surface (1) shown in Fig.1 are also ellipses lying in the planes

$$\sigma_x+\sigma_y=const$$

perpendicular to the axis OD of the ellipsoid from Fig.1. Thus each such an ellipse on the ellipsoid represents the same stress state described in a rotated coordinate system x,y. This follows from the fact that the yield condition (1) is invariant with respect to the rotation of the reference system.

The latter conclusion is of primary importance for programming and interpreting experimental and also numerical studies of the behaviour of yield surfaces of initially isotropic materials. Let us assume, for instance, that the yield stresses of an isotropic metal have been determined by loading a set of tubular specimens each by a different combination of axial force and internal pressure. Such a loading procedure is usually identified with the ellipse BDCB' lying on the ellipsoid shown in Fig.1. In such a case the reference system of coordinates is so chosen that the x-axis is parallel to the logitudinal axis of the tubular specimen and y-axis has the circumferential direction.

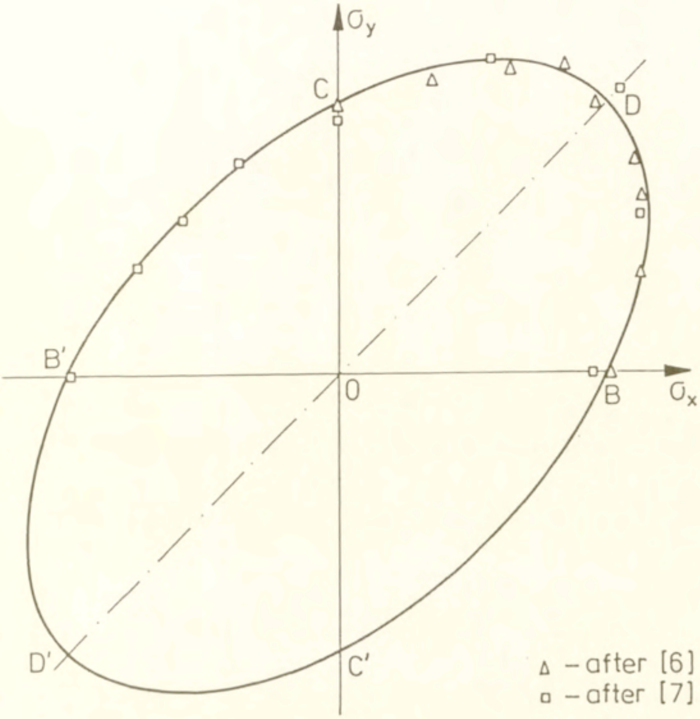


Figure 3:

The yield stresses found in this way for a M-63 brass in [6] and [7] are presented in Fig.3. The experimental points from Fig.3 may be also presented in the plane determined by τ_{xy}-axis and the symmetry axis OD of the ellipsoid from Fig.1, if the axes x and y of reference system will make the angle of 45° with the axial and circumferential directions on the specimen (Fig.4). For such arotated coordinate system the experiment presented in Fig.3 will correspond to the theoretical ellipse DEAE' on the Huber-Mises ellipsoid (Fig.5).

In Fig.6 are presented experimental points from Fig.3 recalculated for a new reference system with the axes x and y making the angle of 45° with the axial direction on the surface of each specimen. Theoretical ellipse DEAE' from Fig.5 is also shown for comparision. Note that to obtain the experimental points such as those shown in Fig.6 with the use of the standard reference system coinciding with the axial and circumferential directions on the surface of the specimens, it would

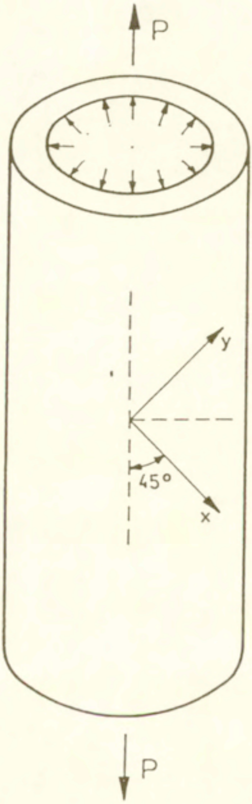


Figure 4:

be necessary to load tubular specimens simultaneously by axial force, a twisting moment and moreover by internal pressure.

Numerous experiments concerning behaviour of yield surfaces were performed by simultaneous loading of thin-walled tubular specimens by a tensile force and a torque. The analysis of the results of such experiment was always performed with the use of a reference system with the coordinate axes coinciding with the axial and circumferential directions. In such a reference frame this mode of loading corresponds to the ellipse AB on the Huber-Mises ellipsoid (cf.Fig.1). An example of the results of experiments performed under simultaneous torsion and tension of thin-walled tubular specimens is shown in Fig.7. If tested material is isotropic such results can be presented in another way by assuming, for instance, for each specimen

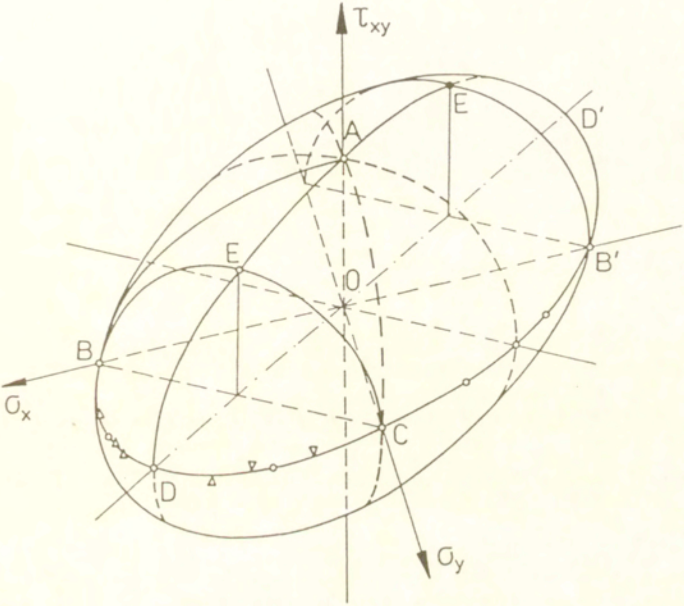


Figure 5:

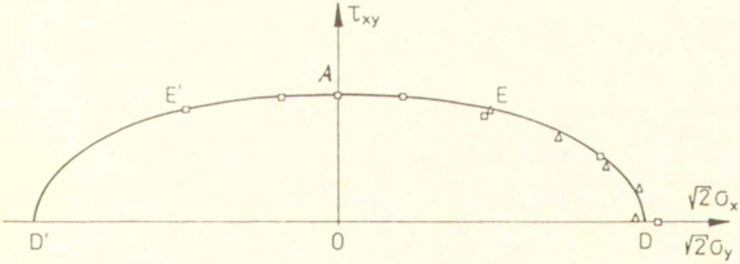


Figure 6:

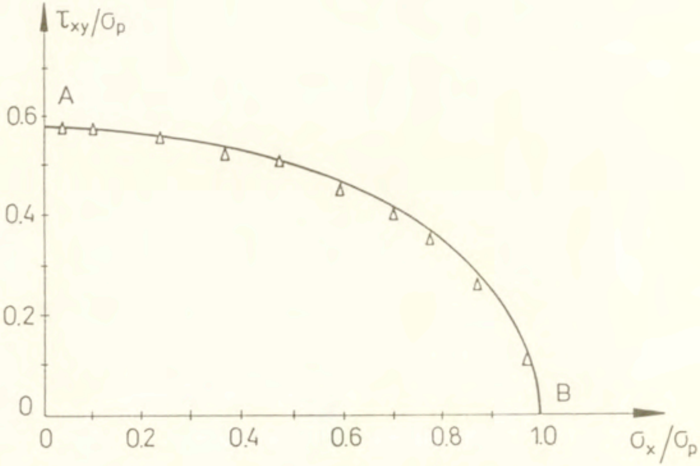


Figure 7:

of the set a reference system x,y coinciding with the directions of principal stresses. Recalculated for such individual reference frames experimental points from Fig.7 are shown in Fig.8. It is seen that in this case the latter representation is less informative than that shown in Fig.7.

When the reference frames are so chosen that for each specimen the axes x and y make the angle 45° with the directions of principal stresses, the recalculated experimental points from Fig.7 correspond to the sector AE of the ellipse DEAE'D' (Fig.1). These points recalculated for such reference frames are shown in Fig.9. Also in this case such a representation is less instructive than the original representation shown in Fig.7.

Analysing more generally the equivalency of various representation of experimental results let us assume, for instance, that the yield surface of an isotropic material has been determined by loading a set of thin-walled tubular specimens by various combinations of a tensile force and a twisting moment. Such a loading procedure corresponds to the segment AB of the ellipse

$$\sigma_x^2 + 3\tau_{xy}^2 = 3k^2$$

lying on the Huber-Mises ellipsoid (cf.Fig.1). The experimetally determined form of the curve AB determines the entire portion of the yield surface shaded in Fig.10a. That portion of the yield surface is generated by ellipses (2) passing through the individual experimental points corresponding to the curve AB (cf.Fig.2).

If the tubular specimens were subject to the simultaneous tension and internal pressure (this corresponds to the segment BD on the Huber-Mises ellipsoid in Fig.1),

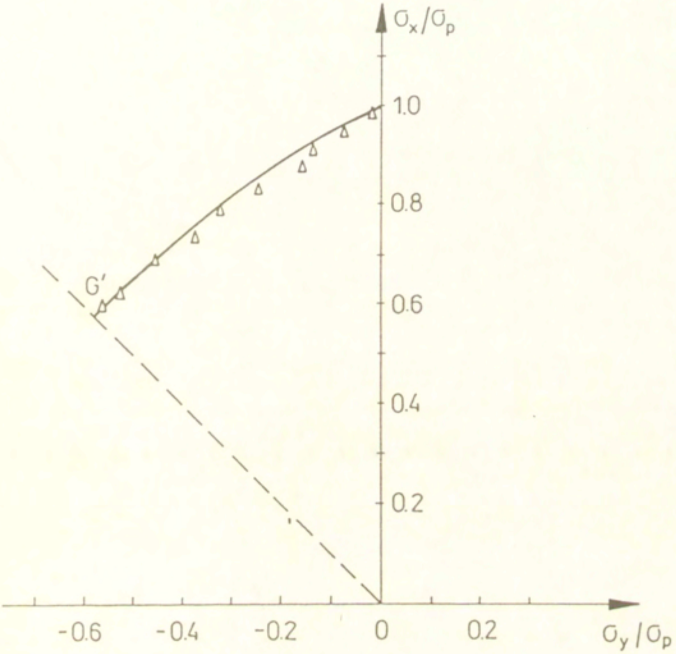


Figure 8:

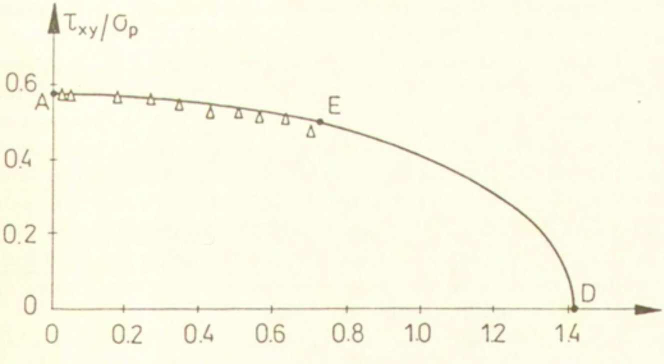


Figure 9:

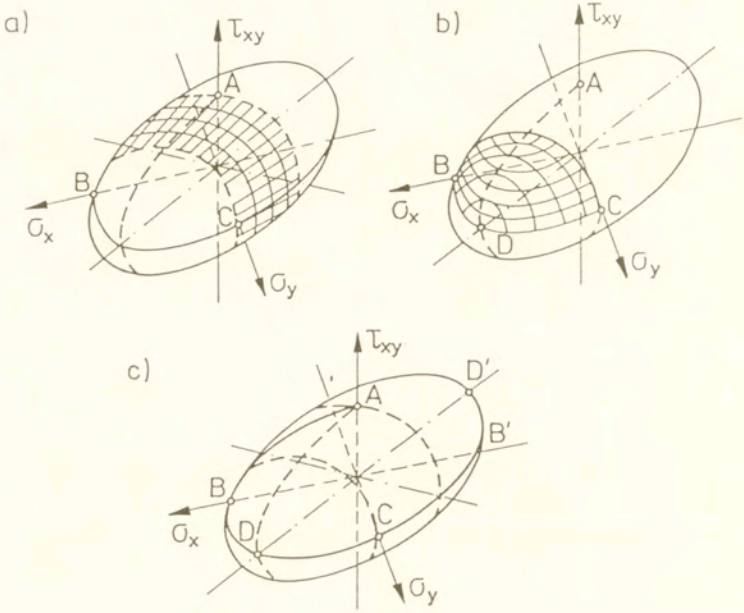


Figure 10:

then by constructing the family of ellipses (2) passing through the experimentally determined points corresponding to BD, the portion of the yield surface shaded in Fig.10b would be obtained.

Carrying out the experiments corresponding to an arbitrary curve which connects points D and D' on the surface (cf.Fig.1), such as the arc DCB'D' in Fig.10c, we obtain the entire yield surface. Additional tests corresponding, for instance, to the arc AB may be considered as a verification whether the material is really isotropic.

Note that this reasoning does not apply to materials exhibiting plastic anisotropy, whether natural or induced by previous plastic deformations. This remark applies in particular to considerations concerning the effect of plastic deformation on the yield surface, or in other words to the analysis of the so-called secondary yield surfaces. Such investigations must be referred to a fixed coordinate system chosen in the beginning of the experimental procedure.

However, there exist a certain practically important type of anisotropy when the procedure described above may be used. Such a case of anisotropy occurs in rolled sheet metals and is referred to as the transversal isotropy. Let the axes of reference

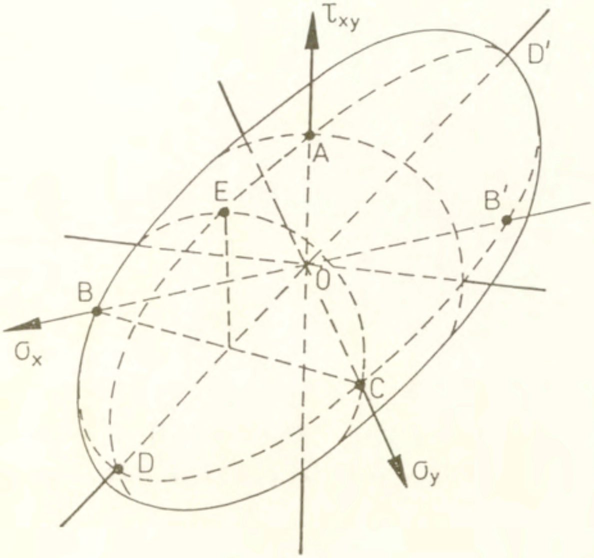


Figure 11:

be so chosen so that the x and y axes lie in the median plane of the sheet and z-axis is normal to that plane. In most cases the plastic properties of the sheet are isotropic in the x,y -plane. The yield stresses of specimens cut out from the sheet in various directions are of the same magnitude Y_0. Of the same magnitude are also absolute values of yield stresses under uniaxial compressive loading. However yield stresses in the z-direction are different from Y_0 in the case of transversal isotropy.

If the Bauschinger effect in z-direction is neglected the yield condition for plane stress state may be written in the following form

$$\sigma_x^2 - \left[2 - \left(\frac{Y_0}{Y_z}\right)^2\right] \sigma_x \sigma_y + \sigma_y^2 + \left[4 - \left(\frac{Y_0}{Y_z}\right)^2\right] \tau_{xy}^2 = Y_0^2 \tag{4}$$

In this condition Y_z is the yield stress in z-direction under uniaxial tension. It represents also the absolute value of yield stresses under uniaxial compression in that direction. In the stress space σ_x, σ_y, τ_{xy} yield condition (4) is represented by the points located on the surface of an ellipsoid shown in Fig.11. For $Y_z > Y_0$ the ellipsoid is more elongated in the OD-direction than that shown in Fig.1 for fully isotropic material. Various methods of measuring the yield stress Y_z are discussed in the previous papers [8] and [9].

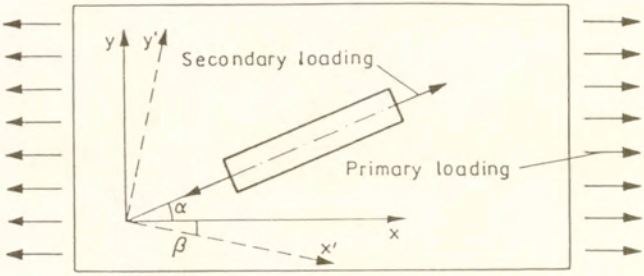


Figure 12:

3 Presentation of the effect of plastic deformation on yield condition in various reference systems

Plastic deformations in metals produces complex changes in the shape and position of the yield surface. These changes are difficult to be described theoretically. Intensive experimental studies are aimed at explaining them. However, there appear certain difficulties in interpreting such experimental results. They are described for example in the previous paper [5] and will not be discussed here.

In section 2 it was shown that if the material in questuion is isotropic in initial state, the orientation of the coordinate system in which the stresses are defined can be chosen arbitrarily. Thus it is possible to present the consecutive yield surfaces deformed after plastic prestraining of the material in various reference systems. In such a manner one can generalize the results of experimental studies of the effect of plastic deformation on yield condition. We shall illustrate this by a number of examples.

Let us begin with a simple method of investigating the effect of plastic deformation on the shape of yield surface used in [10]. Simple rectangular specimens cut out from the sheet metal were tested. The sheet was streched in the x-direction well above initial yield locus. Then after unloading, a series of small rectanular specimens were cut out from the sheet, each inclined at different angle α with respect to the x-direction (Fig.12). These small specimens were tested under uniaxial tensile loading. An example of stress-strain diagram for one of such small specimens is shown in Fig.13. In the figure is also shown the analogous diagram for the specimen cut out in the same direction from non deformed sheet. The two diagrams are displaced one with respect to the other by the value of initial plastic prestrain.

Such diagrams for various angles α were then used to determine the stress cor-

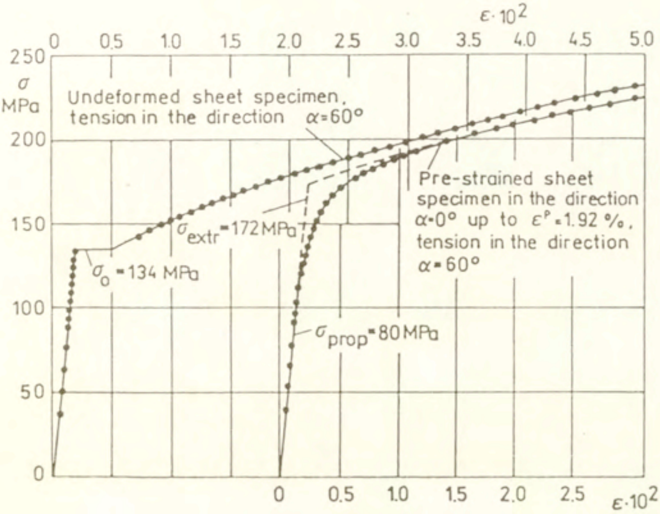


Figure 13:

responding to various definitions of the yield point. Then the yield stresses referred to the x,y coordinate system were calculated from the formulae

$$\sigma_x = \frac{1}{2}\sigma(1 + cos2\alpha),$$
$$\sigma_y = \frac{1}{2}\sigma(1 - cos2\alpha),$$
$$\tau_{xy} = \frac{1}{2}\sigma sin2\alpha \tag{5}$$

Plotting calculated values of yield stresses in the stress space σ_x, σ_y, τ_{xy} we obtain a set of curves (Fig.14) which represent the intersections of various conventional yield surfaces of the prestrained material corresponding to different definitions of yield stresses, with the cone representing uniaxial tensile loading paths (cf.Fig.2). Assuming that $\sigma_2 = 0$ and that $\kappa = \sigma_2/\sigma_1 = 0$ we obtain from Eqn (3) the equation of the cone

$$\sigma_x\sigma_y = \tau_{xy}^2 \tag{6}$$

Fig.14 shows a set of experimentally determined curves projected on the $\sigma_x\sigma_y$ -plane and on another plane perpendicular to the bisector of the right angle between the coordinate axes in the $\sigma_x\sigma_y$ -plane. Point B denotes the end of the path OB of initial loading of the sheet. The initial yield curve before prestraining is shown by dashed line.

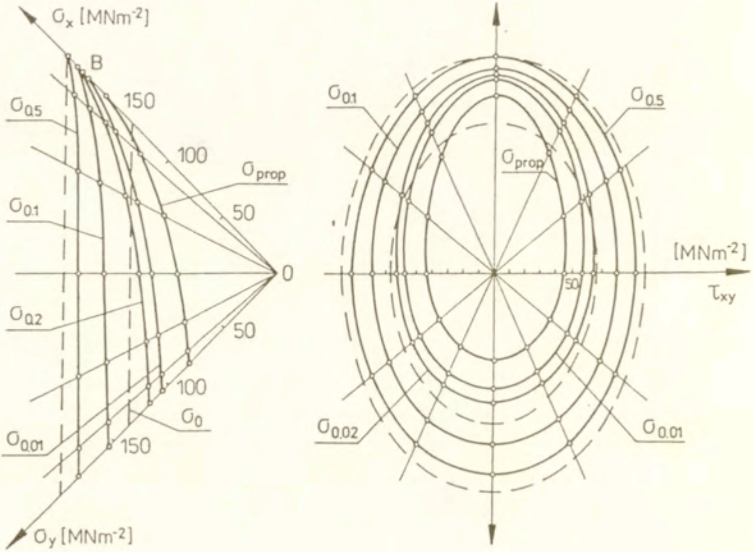


Figure 14:

Experimental results shown in Fig.14 can be represented in another various coordinate systems rotated by an angle β with respect to the original system x,y. Rotation of the coordinate system in the median plane plane of the sheet causes that in the stress space the end point of the vector OB characterizing the initial loading of the sheet moves along the ellipse corresponding to uniaxial tension (Fig.15).

The experimental lines shown previously in Fig.14 for the non-rotated coordinate system are represented in Fig.16 for the coordinate system x,y rotated by the angle $\beta = 15^o$ with respect to the original one. Such a rotation of the coordinate system corresponds to the prestressing path OB_1 in the new system (cf.Fig.15). Similarly the yield curves shown in Fig.17 correspond to $\beta = 30^o$ and the prestressing path OB_2. In the Fig.18 are presented yield curves for rotation angle $\beta = 45^o$ and the prestressing path OB_3.

Since the material was found to be initially isotropic all four representations are fully equivalent because the coordinate system could be chosen arbitrarily.

This simple method of experimental investigation of the effect of plastic deformation on the shape of the yield surfaces was recently extended by R.Szczebiot [11]

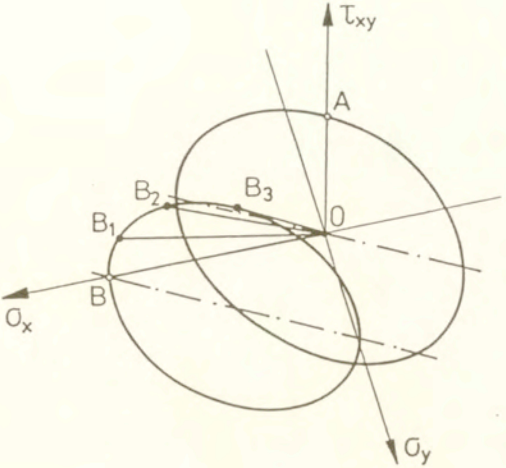


Figure 15:

on the region of compressive stresses in the stress space. Tensile tests for specimens cut out in different directions from a prestressed sheet were performed in the same manner as in [10]. However, now they were complemented by compression tests with the use of another set of specimens cut out in the same directions from the same prestressed large specimen.

As the material a sheet 3 mm thick of the aluminium alloy PA2N-M3 (Al2%Mg) was used. Large specimens cut out in the rolling direction, assumed by the author as the x-direction, were plastically deformed each by different stresses $\sigma_A = 124.5$ MPa, $\sigma_B = 154.6$ MPa, $\sigma_C = 185.5$ MPa respectively. These stress levels were well above the conventional yield stresses $\sigma^o_{0.5} = 100$ MPa for the offset strain 0.5 percent of the sheet in the initial state, in which the sheet was found to be fully plastically isotropic in its plane. No Bauschinger effect was observed in the sheet before prestraining.

Compression tests on small specimens cut out from the sheet were performed with the use of special testing device preventing thin specimens from buckling. This device was designed by L.Dietrich and K.Turski [12] - see also [5].

In Fig.19 are presented original experimental curves given in [11], were the prestressing uniaxial tension OB was chosen to coincide with the assumed x-direction in the sheet's plane. Thus these curves correspond to the case when prestressing level was equal to $\sigma_B = 154.6$ MPa.

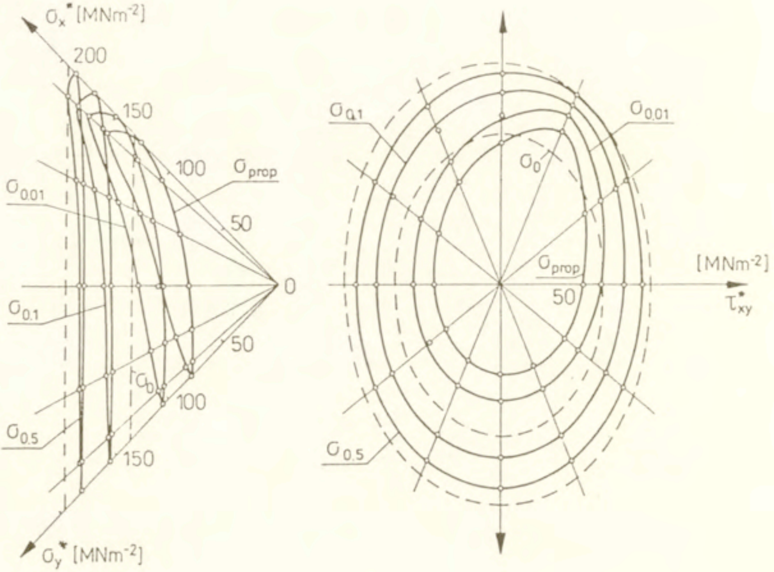


Figure 16:

Note that the projections of the curves shown on the left-hand side of Fig.19a and their projections shown in Fig.19b are analogous to these presented in Fig.14 for another material. On the right hand side of Fig.19a and in Fig.19c are shown projections of the conventional yield curves for the prestressed material afterwards loaded by uniaxial compression in different directions with respect to the previously chosen x-axis of the reference system. In geometrical terms the two sets of experimental conventional yield curves in the tension and compression quadrants of the stress space represent the intersections of the deformed conventional yield surfaces of prestressed material with the cones

$$\sigma_x \sigma_y = \tau_{xy}^2$$

on both sides of the symmetry axis OA in the stress space (cf.Fig.1).

Comparision of the experimental curves σ_{prop}, $\sigma_{0.01}$ and $\sigma_{0.02}$ on both sides of the symmetry axis demonstrates the clearly visible Bauschinger effect induced in the sheet by previous plastic deformation.

In Fig.20 are shown the same experimental results referred to another reference system x,y rotated by the angle $\beta = 45°$ with respect to that assumed for the

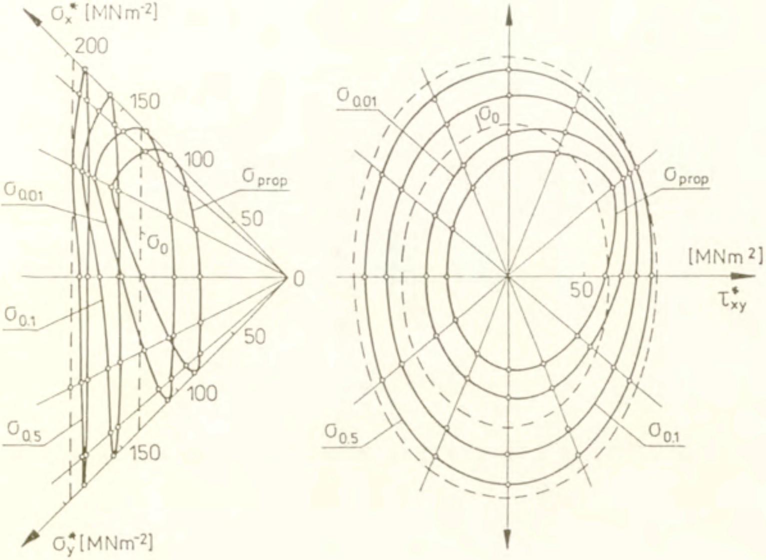


Figure 17:

previous representation of results in Fig.19. Thus now the x and y axes make the angle of 45° with the prestressing direction. In such a rotated reference system the initial yield surface was pushed from inside along the stright line OE (cf.Fig.1) up to the end point B of the prestressing path OB.

This bulging of the yield surface caused by previous plastic deformations is even more distinctly demonstrated for still larger prestressing level by the stresses $\sigma_C =$ 185.5 MPa. In Fig.21 are presented original experimental curves taken from [11]. The x-axis of the reference system coincides with the direction of the prestressing path OC. Fig.22 presents the same experimental results in the coordinate system rotated by an angle of 45° with respect to the original one.

Evolution of the yield surface during the process of plastic deformation of the material may be observed if the corresponding conventional yield curves for the consecutive stages of prestraining are presented in the same figure, as it has been done in Fig.23 for the $\sigma_{0.02}$ yield curves in the original coordinate system (cf.[11]). The mode of evolution is even more clearly visible if the same experimental curves are presented in another coordinate system rotated by an angle of 45° (Fig.24).

As a next example let us transorm the experimental conventional yield curve

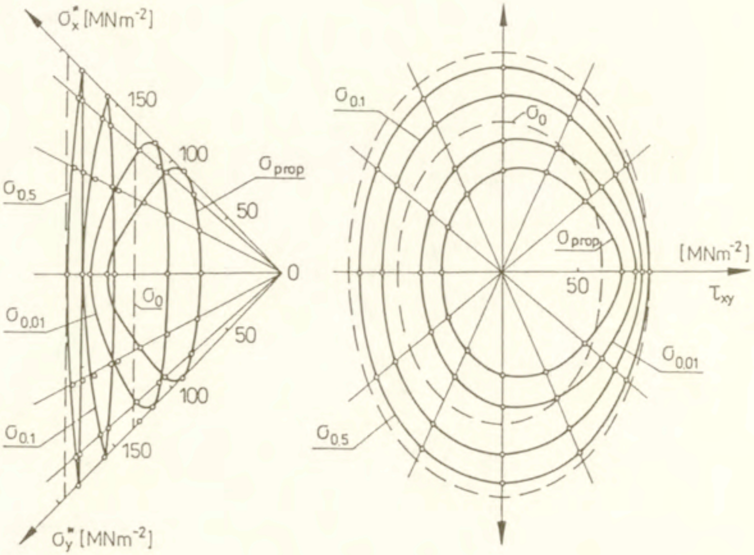
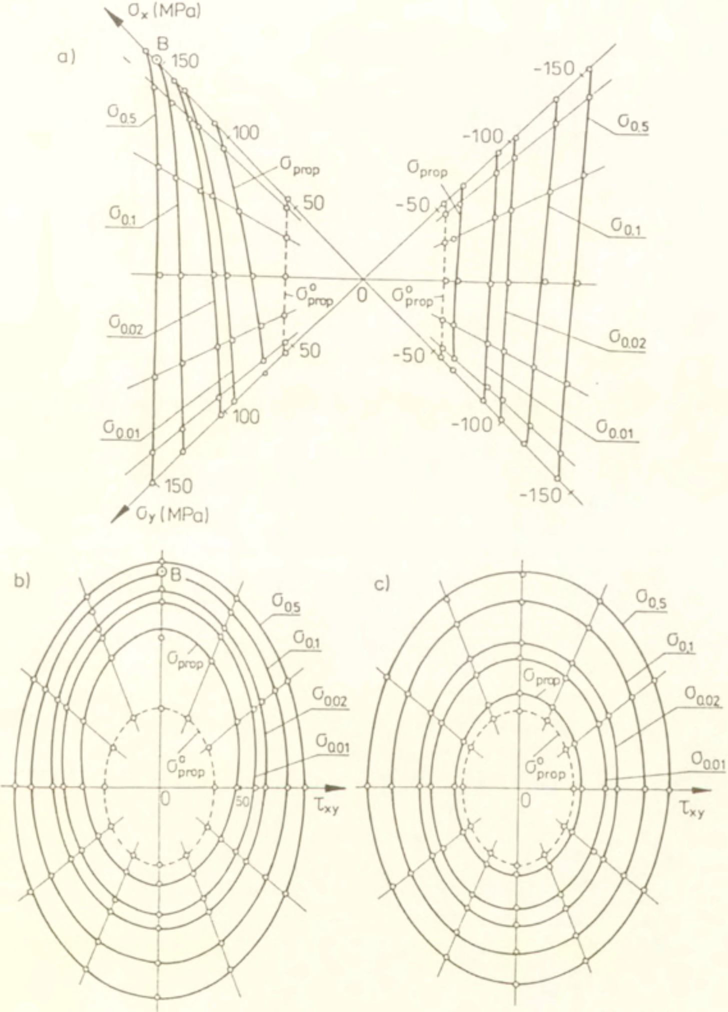


Figure 18:

$\sigma_{0.01}$ obtained by R.Kiryk [13] for the duralumin type alloy PA6. A thin walled tubular specimen was prestressed by uniaxial tension in axial direction far beyond the initial yield stress and then unloaded. Next the conventional yield curve for such prestressed material was determined by consecutive loading of the specimen by various combinations of axial force and torque. The $\sigma_{0.01}$ yield curve is shown in Fig.25 in the standard for such tests coordinate system in which the x-axis is parallel to the axis of the tube. In Fig.26 are presented in two projections these experimental results in another coordinate system x,y rotated by an angle of 45^o with respect to original system from Fig.25.

Since the material in the initial state displayed fully isotropic plastic properties the initial yield surface shown in Fig.1 is valid for any arbitrarily oriented coordinate system x,y. Thus the prestressing path OB in the original reference system corresponds to the path OE in the coordinate system rotated by an angle of 45^o.

Variously oriented reference systems may be used when experimental results such as those shown in Fig.25 are presented in the stress space. Still another reference system rotated by an angle of 22^o30 is used in Fig.27 for presentation of the same experimental results. Now the prestressing path passes through origin O and a


a)
σx (MPa)
B
150
100
50
σ0.5
σprop
σ0.1
σ0.02
σ0.01
0
σ°prop
σ°prop
50
100
150
σy (MPa)
-150
-100
-50
-50
-100
-150
σprop
σ0.5
σ0.1
σ0.02
σ0.01
b)
B
σ0.5
σ0.1
σ0.02
σ0.01
σprop
σ°prop
0
50
τxy
c)
σ0.5
σ0.1
σ0.02
σ0.01
σprop
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0
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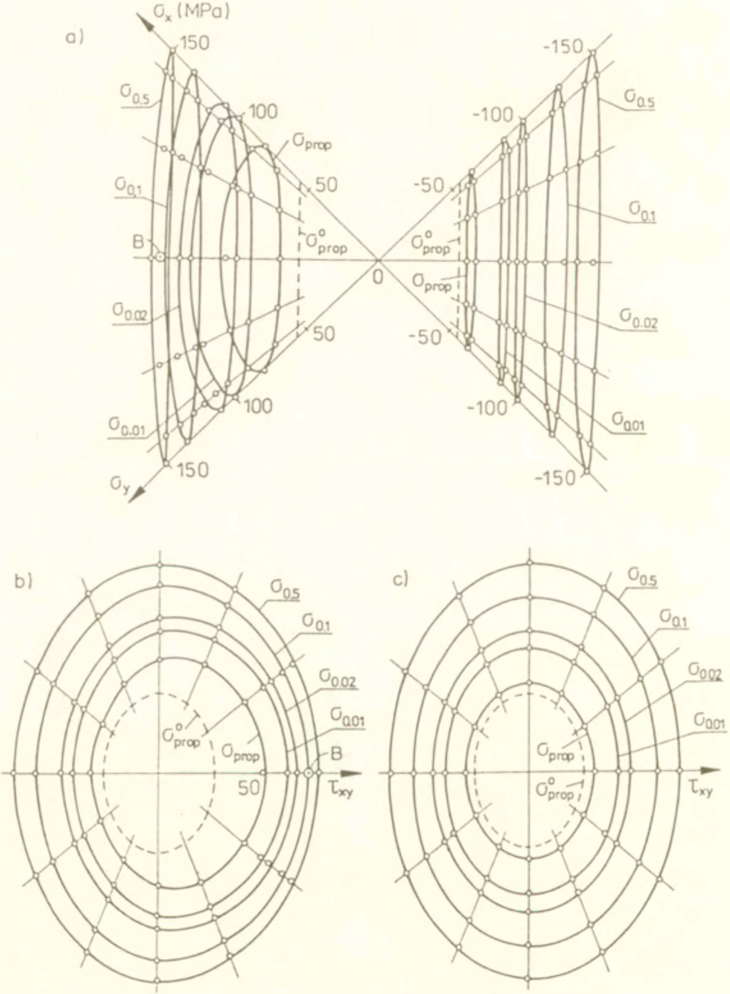
Figure 19:


a)
σx (MPa)
150
100
50
σ0.5
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B
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0
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50
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-150
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σ0.01
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b)
σ0.5
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σ°prop
σprop
B
50
τxy
c)
σ0.5
σ0.1
σ0.02
σ0.01
σprop
σ°prop
τxy

Figure 20:

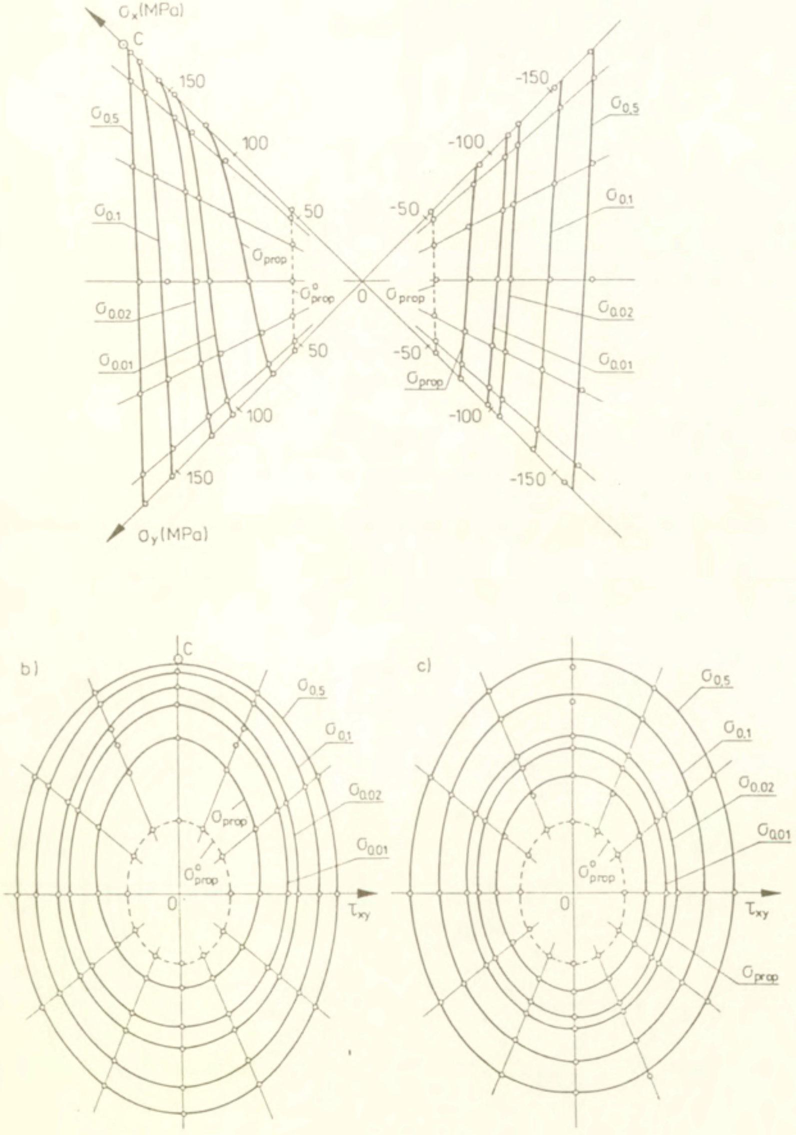
σx(MPa)
C
150
100
50
σ0,5
σ0.1
σprop
σ°prop
0
σprop
σ0.02
σ0.01
50
100
150
σy(MPa)
-150
-100
-50
σ0,5
σ0.1
σ0.02
σ0.01
-50
σprop
-100
-150
b)
C
σ0,5
σ0,1
σ0.02
σ0.01
σprop
σ°prop
0
τxy
c)
σ0,5
σ0,1
σ0.02
σ0.01
σ°prop
0
τxy
σprop

Figure 21:

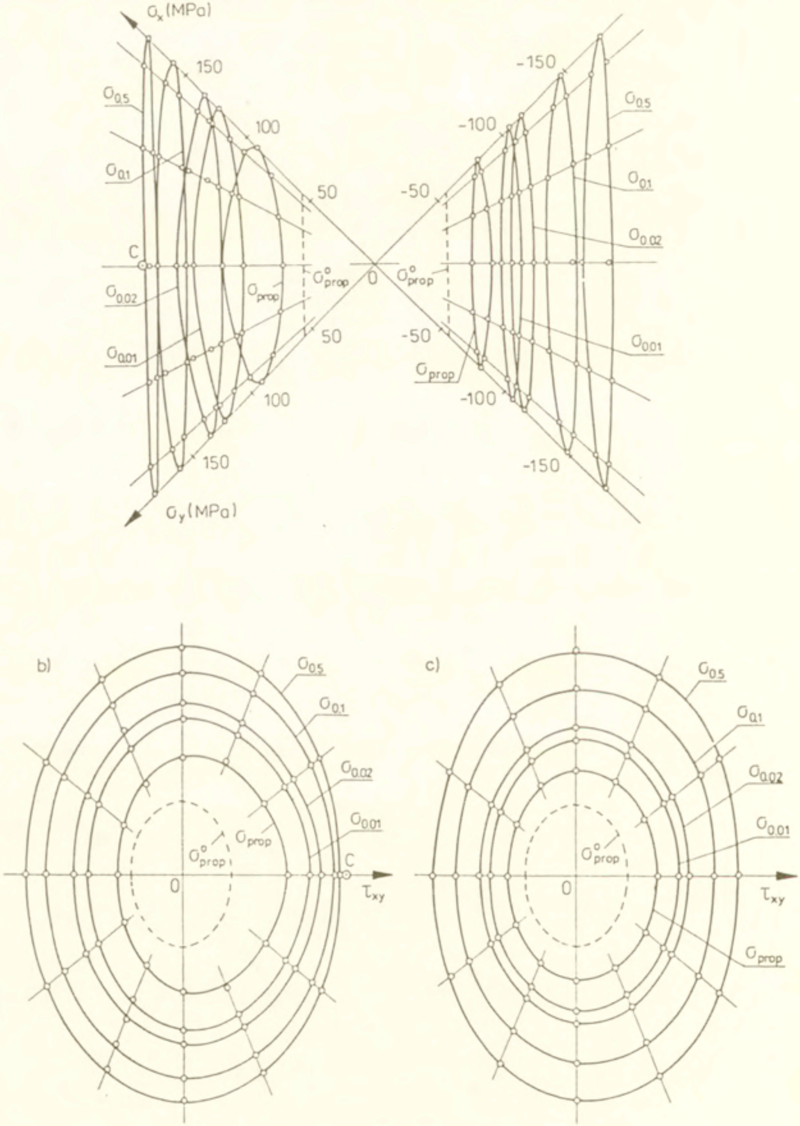
σ_x (MPa)
150
100
50
$\sigma_{0.5}$
$\sigma_{0.1}$
C
$\sigma_{0.02}$
$\sigma_{0.01}$
σ_{prop}
σ^o_{prop}
0
σ^o_{prop}
50
100
150
σ_y (MPa)
-150
-100
-50
$\sigma_{0.5}$
$\sigma_{0.1}$
$\sigma_{0.02}$
$\sigma_{0.01}$
σ_{prop}
-50
-100
-150
b)
$\sigma_{0.5}$
$\sigma_{0.1}$
$\sigma_{0.02}$
$\sigma_{0.01}$
σ_{prop}
σ^o_{prop}
0
C
τ_{xy}
c)
$\sigma_{0.5}$
$\sigma_{0.1}$
$\sigma_{0.02}$
$\sigma_{0.01}$
σ^o_{prop}
0
τ_{xy}
σ_{prop}

Figure 22:

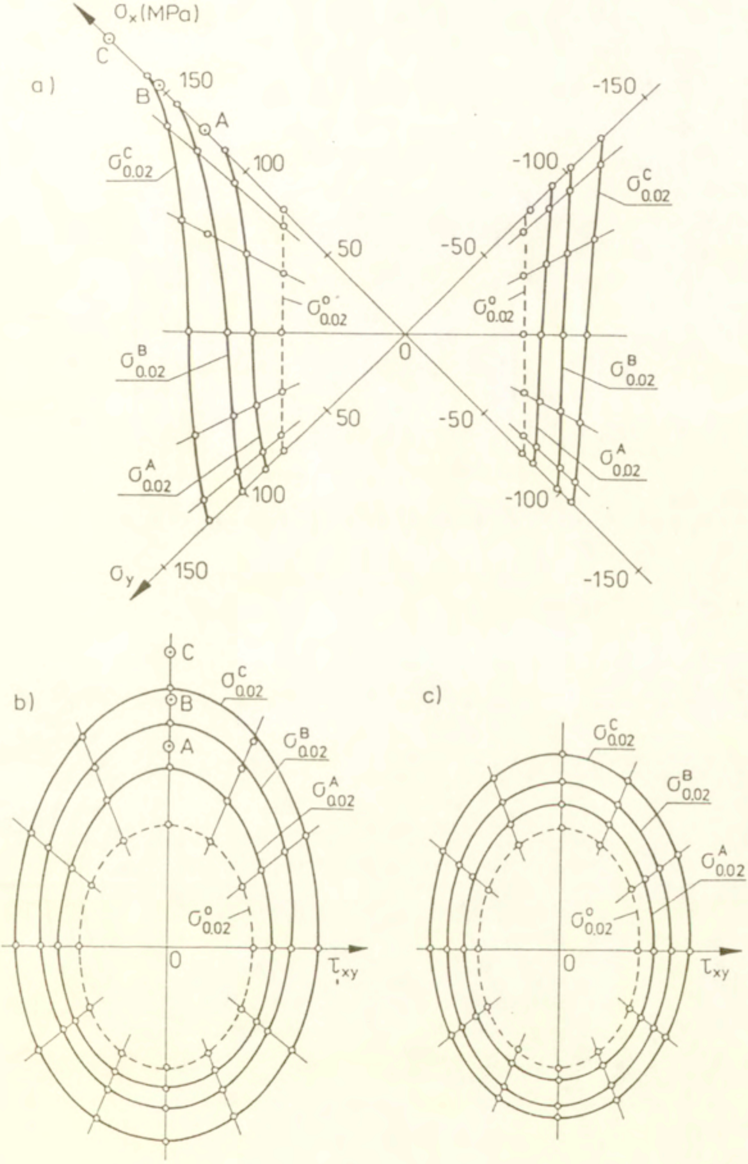
a)
σ_x (MPa)
C
B
A
150
100
50
0
50
100
150
σ_y
-150
-100
-50
-50
-100
-150
$\sigma^C_{0.02}$
$\sigma^B_{0.02}$
$\sigma^A_{0.02}$
$\sigma^o_{0.02}$
b)
c)
τ_{xy}
0

Figure 23:

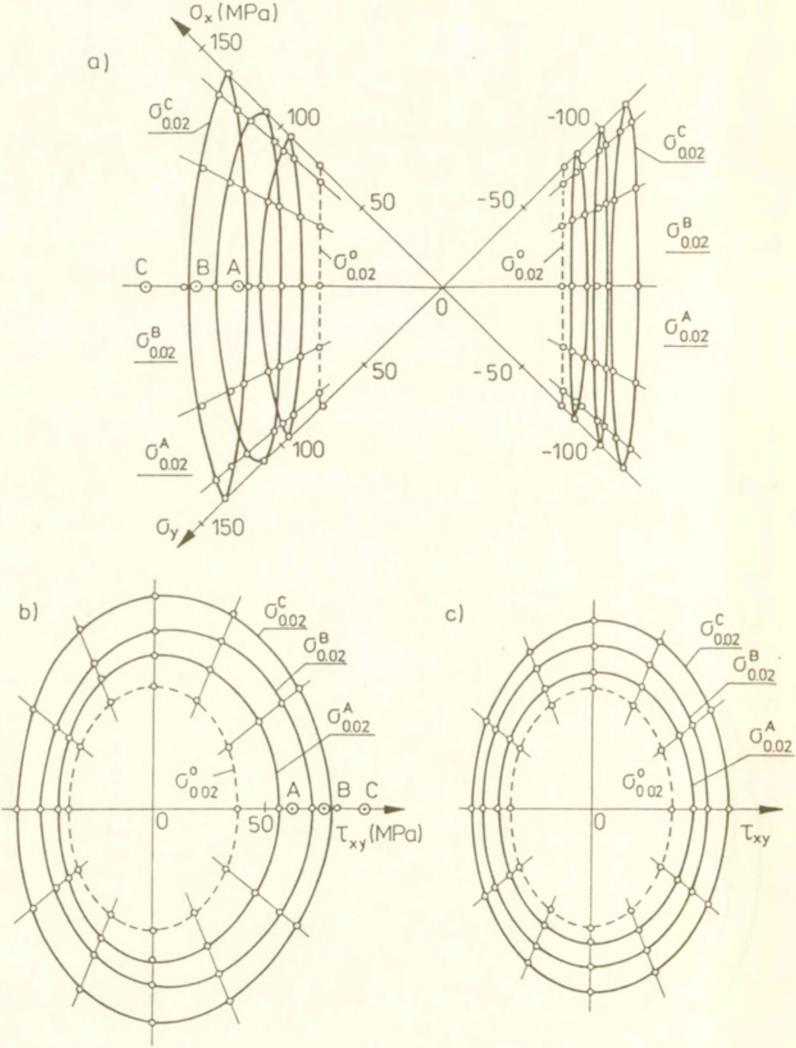
a)
σx (MPa)
150
100
50
-100
-50
σC0.02
σB0.02
σA0.02
σ00.02
C
B
A
0
σy
b)
c)
50
τxy (MPa)
τxy

Figure 24:

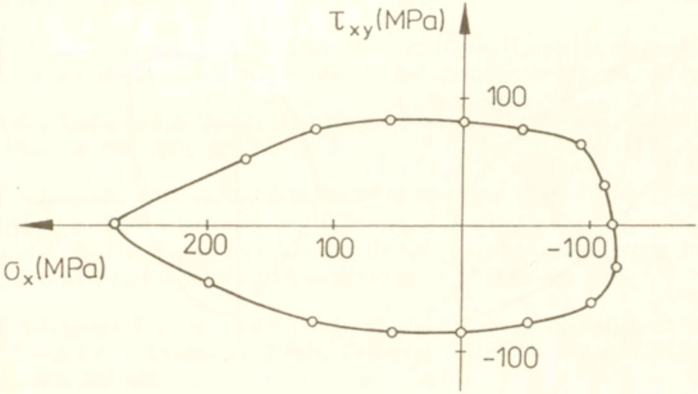

Figure 25:

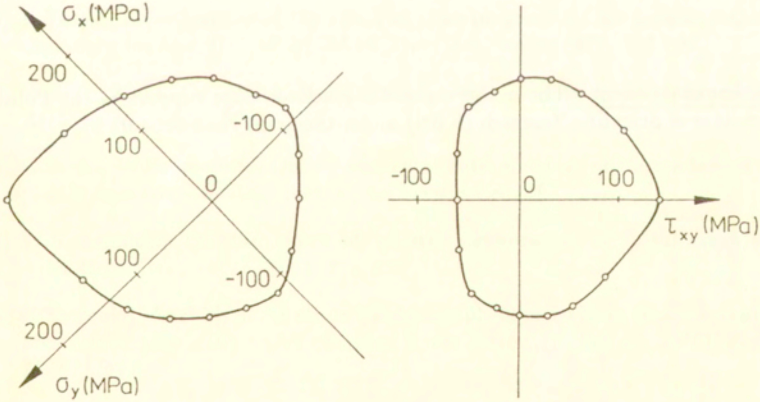

Figure 26:

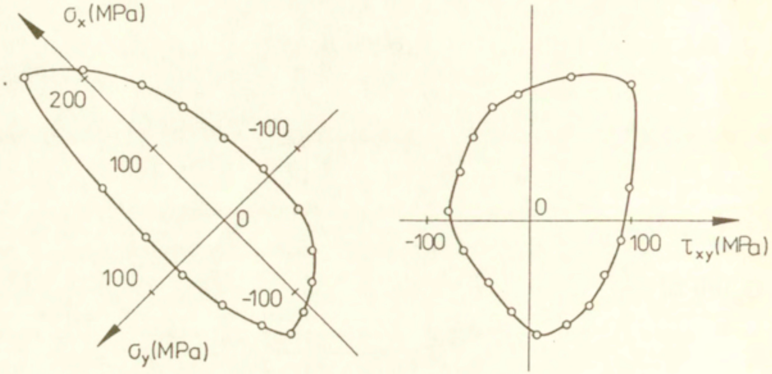

Figure 27:

certain point lying on the ellipse BLENC in Fig.1.

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