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Technical Working Area 13
Low Cycle Fatigue

A PROCEDURE FOR THE MEASUREMENT OF MACHINE ALIGNMENT IN AXIAL TESTING

Report No. 42
ISSN 1016-2186
February 2003

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A PROCEDURE FOR THE MEASUREMENT OF MACHINE ALIGNMENT IN AXIAL TESTING

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A Procedure for the Measurement of Machine Alignment in Axial Testing

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ABSTRACT

This document describes a method for the measurement and classification of machine alignment of uniaxial test systems. It applies to any uniaxial test system for static or dynamic loading, in tension, compression, or tension-compression. The method applies primarily to test systems for metallic materials.

0 INTRODUCTION

Alignment of the axial test machine load-train is critical to many types of mechanical testing of materials including tension, compression and fatigue [1-3]. This document describes a method for verifying the machine alignment by means of measuring the bending on the surface of a strain-gauged specimen. The method separates the bending contribution due to misalignment in the machine's load train components from that due to inherent errors in the strain-gauged specimen. The machine alignment is characterised according to the machine component only and thus excludes any measurement bias in the strain-gauged specimen.

1 SCOPE

This Guide describes a method for the measurement of machine alignment measurement of axial (tension, compression or tension-compression) test systems. It applies primarily to systems for testing cylindrical specimens (with either straight or button-head ends) or rectangular specimens of metallic materials. It is not recommended that this measurement technique is used for specimens with threaded ends. The procedure described herein may be adapted for use with notched specimens and non-metallic materials.

2 DEFINITIONS

2.1 Alignment

The geometrical conformance between the axes of a testing machine load train components. Departure from such conformance may introduce bending moments into the specimen during tensile or compressive loading.

2.2 Alignment cell

A carefully machined test specimen instrumented with strain gauges for use in the measurement of alignment of the testing machine. An alignment cell is meant for use in successive alignment verifications and, therefore, must only be subjected to elastic deformations.

2.3 Axial strain, *a*

The average longitudinal axial strain measured at the surface of the alignment cell by a set of strain gauges with transverse axes located in the same measurement plane.

2.4 Bending strain, *b*

The difference between the local strain measured by a strain gauge and the axial strain. In general, the bending strain varies from point to point around and along the surface of the alignment cell.

2.5 Force, *F*

The axial force applied to the alignment cell, tensile being considered positive and compressive being considered negative.

2.6 Maximum bending strain, b_{max}

The largest value of the tensile bending strain in the two cross-sections at which bending is measured. It is a vector with magnitude b_{max} and angle θ.

2.7 Percent bending, β

The absolute value of maximum bending strain times 100 and divided by the axial strain. It is the higher value of percent bending determined on the two cross-sections at which bending is measured.

2.8 Measurement plane

The transverse plane in the alignment cell in which the transverse axes of the strain gauges are positioned; the upper plane corresponds to gauges A1 to A4 and the lower plane corresponds to gauges B1 to B4 (Figure 1).

2.9 Modulus of elasticity, *E*

The ratio of the stress to the corresponding strain below the proportional limit.

2.10 Parallel length, l_p

The length on an alignment cell of the parallel reduced cross-sectional part.

2.11 Proportional limit

The stress or strain limit that a material can sustain without any deviation from proportionality of stress to strain (Hooke's law).

2.12 R-direction

A fixed reference coordinate with respect to the frame of the testing machine - typically it is the direction from the specimen axis towards the front of the machine (see Figure 2).

2.13 Specimen orientations

Specimen orientations, about its vertical axis, that defines the position of gauge A1 with respect to the R-direction (see Figure 2)

2.14 Strain-gauge axial separation, l_g

The axial distance on the alignment cell between the upper and lower strain measurement planes (see Figure 1).

2.15 Strain-gauge transverse separation, w_g

The distance on the broad face of a thin rectangular alignment cell between the centres of the strain gauges; see Figure 1(c).

3 SYMBOLS

For the purpose of this Guide the following symbols and designations apply.

Symbol	Designation
a	Axial strain
A1, A2, A3, A4	Numbers of individual gauges at the upper measurement plane
b	Local bending strain
b_{mc}	Local bending strain component due to machine misalignment
b_{sp}	Local bending strain component due to specimen's errors
b_{max}	Maximum bending strain measured on the specimen's surface
$b_{max.mc}$	Maximum bending strain component due to machine misalignment
$b_{max.sp}$	Maximum bending strain component due to specimen's errors
B1, B2, B3, B4	Numbers of individual gauges at the lower measurement plane
d	Diameter of reduced section of cylindrical cells
D	Diameter of grip end of cylindrical cells
E	Modulus of elasticity
l_g	Strain-gauge axial separation (= 0.75 l_p)
l_p	Parallel length
F	Applied axial force
r	Transition radius between the parallel section and the grip ends
t	Thickness of rectangular cells
w	Width of reduced section of rectangular cells
w_g	Strain-gauge transverse separation (= 0.75 w)

W	Width of grip end of rectangular cells
β	Maximum percent bending measured on the specimen's surface
β_{mc}	Component of maximum percent bending due to the machine misalignment
β_{sp}	Component of maximum percent bending due to inherent errors in the strain-gauged specimen (or alignment cell)
ε_1, ε_2, etc	Strain readings of individual gauges
θ	Angle (clockwise when seen from above) of the maximum bending strain vector with respect to the R-direction

4 MEASUREMENT REQUIREMENTS

4.1 Testing machine

The machine should have great lateral rigidity and accurate alignment between the test space support references. The load train should be as short and as stiff as possible. *It is important that errors in parallelism (angular offsets) and in concentricity (lateral offsets) of the components of the load train are reduced to a minimum before carrying out the present procedure.* Machine alignment may be improved by iterative adjustment to the axial and angular positions of the load train components using an appropriate alignment fixture.

The specimen's gripping device should be designed so that during the gripping operation no torsion stresses are introduced into the specimen and that the assembly of the specimen to the gripping device is reproducible. It is therefore necessary to limit the number of components of which these gripping devices are composed in order to reduce the number of mechanical interfaces to a minimum.

4.2 Alignment cell

4.2.1 Material

A suitable material for an alignment cell should have:

(1) a sufficiently high elastic working range;
(2) an elastic modulus within the range (200 - 250 GPa); and
(3) a high degree of metallurgical stability coupled with freedom from appreciable residual stress in order to ensure long-term dimensional stability.

Oxidation resistant, high strength steels and superalloys are ideal candidates.

4.2.2 Geometry and design

The alignment cell may be of a cylindrical or a rectangular type. It should fit into the machine grips in the same way as the test specimen, so that use of special adaptors is avoided.

Figures 3 and 4 show the machining requirements in terms of concentricity, parallelism and perpendicularity for the two basic alignment cell geometries.

Cells possessing other dimensions may be used successfully within the scope of this Guide. However, significant variations in dimensions might preclude direct comparison with measurements from alignment cells with the recommended dimensions. Table 1 below gives the recommended proportions for both types of alignment cells.

Table 1. Proportions of alignment cells

Dimension	Requirement	Comments
w	$\geq t$	
d	≥ 5 mm	A maximum diameter of 10 mm is recommended
D		A minimum dimension of $2.5d$ to $3.5d$, depending on the material, is recommended
l_p	$\geq 2d$	
	$\geq 2t$	
r	$> 2d$	$2d < r \leq 4d$ is adequate for most materials
	$4t$ to $8t$	
t	≥ 2 mm	
W		A dimension of $3t$ to $5t$ but not less than $1.5w$ is recommended

4.2.3 Machining

Alignment cells should ideally be made using precision grinding. Small and decreasing cuts with an adequate supply of coolant should be used for finishing to minimise introducing residual stresses and to reduce any effects of the machining process on the metallurgical structure and properties. Care must be exercised in the machining of the reduced section to avoid undercutting at the ends of the parallel portion. For effective bonding of strain gauges, the optimum surface finish for the alignment cell should be in the range 0.4 to 0.8 micrometers.

4.2.4 Inspection

The alignment cell should be carefully inspected with an optical comparator or a shadowgraph before strain gauges are attached to ensure that dimensional and concentricity requirements are met.

4.3 Strain gauges

4.3.1 Selection

Strain gauges having active lengths of approximately 0.1 l_p or less should be used. Gauges of between 0.38 and 1.57 mm gauge length and between 0.51 and 1.57 mm grid widths are currently commercially available and are suitable for the purposes of this measurement. It is recommended that the gauge is as small as practically possible in order to minimise any effects due to strain averaging. All strain gauges used should be from the same batch. The bending parameters in this Guide are determined from the ratios of the measured strains and they should not, therefore, be affected by temperature changes. Temperature-compensated gauges matched to the alignment cell material are however preferred, especially if accurate determination of the absolute axial average strain, such as in modulus measurement, is also needed.

4.3.2 Bonding

Figure 1 shows the recommended strain gauge numbering systems and bonding locations. An array of at least eight strain gauges is recommended. The gauges are to be arranged in two sets of four with each set mounted on one of two strain measurement planes. In Figure 1(a) the strain gauges are equally spaced, i.e. 90^o apart, around the circumference of the alignment cell. The configuration shown in Figure 1(b) is suitable for rectangular cells with a width-to-thickness ratio $w/t < 3$. For higher (w/t) values the configuration in Figure 1(c) is recommended. In Figure 1(c) the gauges are placed in pairs of back-to-back sensors that are equidistant from the centre line of the alignment cell.

With reference to Figure 1, the table below gives the recommended locations for positioning the strain gauges on the surface of the alignment cells.

Table 2. Locations of strain gauges

Dimension	Requirement
l_g	= 0.75 l_p
w_g	= 0.75 w

Note 1: The distance l_g = 0.75 l_p represents the maximum feasible separation that should avoid interaction of strain gauges with stress concentration effects associated with the change of section at the ends of the specimen's parallel length.

Note 2: A third set of gauges, located at the geometrical centre of the alignment cell may be used. However, it should be noted that the maximum bending strain would normally be determined by one of the sets located near the ends of the specimen's parallel length. There are some instances where the maximum bending appears to occur at the middle of the specimen. However, in these circumstances, this is most likely to be due to errors in the measurement. The difference between the maximum bending strain determined by the middle set of gauges and that determined by the sets of gauges at the ends of the specimen is expected to be insignificantly small. Significant savings of cost and effort are made by the use of only two sets of gauges.

4.3.3 Alignment (of strain gauges)

Care in strain-gauging the alignment cell cannot be over emphasised. It is essential to ensure that the gauges are bonded (using the manufacturer's recommended procedures) at the specified locations to within ± 0.10 mm and that their measurement axes are aligned to within ± 2° of the longitudinal axis of the alignment cell. After installation of the gauges, their alignment should be checked and confirmed using a suitable instrument such as an angular optical projector or a circular graticule in a low-power microscope before applying any protective coating.

4.3.4 Adhesion

Use an adhesive such as a heat cured epoxy phenolic type to ensure long-term stability. Care should be taken to avoid the use of curing temperatures that could alter the metallurgical characteristics of the alignment cell material.

4.3.5 Coating

It is essential to protect strain gauges and adhesives from effects due to moisture and other degrading contaminants. It is recommended, therefore, that after installation of the gauges a layer of a protective coating material such as strain-gauge-grade silicone rubber be applied.

4.3.6 Lead wires

A temperature-compensating three or four lead wire system should be used in ¼ bridge configuration.

4.3.7 Strain measuring and recording equipment

All strain measuring equipment and data acquisition systems should be calibrated as appropriate and typically have a resolution of 1 micro-strain and an accuracy to within ± 0.5% of indicated reading or ± 3 micro-strain, whichever is greater.

5 ALIGNMENT MEASUREMENT CALCULATIONS

5.1 Case of cylindrical alignment cells

For any set of four gauges in the same cross-sectional plane, the average axial strain is:

$$a=(\varepsilon_1+\varepsilon_2+\varepsilon_3+\varepsilon_4)/4 \tag{1}$$

and the local bending strains are:

$$b_1=\varepsilon_1-a \tag{2}$$

$$b_2=\varepsilon_2-a \tag{3}$$

$$b_3=\varepsilon_3-a \tag{4}$$

$$b_4=\varepsilon_4-a \tag{5}$$

The maximum bending strain is given by:

$$b_{max} = 1/2\sqrt{(b_1-b_3)^2+(b_2-b_4)^2} \tag{6}$$

Where b_{max} is the maximum bending strain in the cross-section where the gauges are located. Note that the strain gauge readings are in units of strain and compressive strains are negative.

The angular position, θ, of the maximum bending strain with respect to the R-direction is determined as follows:-

For Orientation 1 (Gauge 1 is at 0 degrees):

$$\theta = sign(b_2-b_4)\times acos\left(\frac{b_1-b_3}{2b_{max}}\right) \tag{7}$$

For Orientation 2 (Gauge 1 is at 180 degrees):

$$\theta = sign(b_4-b_2)\times acos\left(\frac{b_3-b_1}{2b_{max}}\right) \tag{8}$$

For Orientation 3 (Gauge 1 is at 90 degrees):

$$\theta = sign(b_1-b_3)\times acos\left(\frac{b_4-b_2}{2b_{max}}\right) \tag{9}$$

For Orientation 4 (Gauge 1 is at 270 degrees):

$$\theta = sign(b_3 - b_1) \times a\cos\left(\frac{b_2 - b_4}{2b_{max}}\right) \tag{10}$$

Where θ is in clockwise rotation if positive and anticlockwise if negative.

Note: It is not unusual for θ to change during the measurement by a few degrees as the applied force or axial strain is increased or decreased. Sudden or erratic changes in θ, however, may indicate mechanical instability in the loading system.

The maximum percent bending, β, is:

$$\beta = abs\left|\frac{b_{max}}{a}\right| \times 100 \tag{11}$$

Where b_{max} is the highest value determined on the strain-gauge measuring planes.

Note: the above maximum percent bending represents the highest value measured within the strain-gauge axial separation, l_g, of the alignment cell. The absolute maximum bending strain on the alignment cell surface may however take place outside the distance l_g, see Appendix 3 in Reference 1 for more discussion. Such details, however, are not significant for practical measurements and therefore are ignored here.

The above calculations are included in the spreadsheet ALIGNCAL [4].

5.2 Case of thick rectangular alignment cells

For thick rectangular alignment cells, Figure 1(b), the average axial strain and the local bending strains are calculated according to the equations given above for cylindrical alignment cells. The maximum bending strain in this case is calculated from the following equation:

$$b_{max} = \frac{|b_1 + b_2|}{2} + \frac{|b_3 + b_4|}{2} \tag{12}$$

Percent bending is calculated from equation 11.

5.3 Case of thin rectangular alignment cells

For thin rectangular alignment cells, Figure 1(c), an equivalent system to Figure 1(b) is established where the equivalent strains are located at the centre of the specimen's four faces. The corresponding equations are:

$$\varepsilon_{1e} = (\varepsilon_1 + \varepsilon_2)/2 \tag{13}$$

$$\varepsilon_{2e} = a + [(\varepsilon_1 + \varepsilon_3)/2 - a](w / w_g) \tag{14}$$

$$\varepsilon_{3e} = (\varepsilon_3 + \varepsilon_4)/2 \tag{15}$$

and

$$\varepsilon_{4e} = a + [(\varepsilon_2 + \varepsilon_4)/2 - a](w / w_g) \tag{16}$$

where a is the axial strain, given by equation 1, w is the width of the broad face of the alignment cell and w_g is the strain-gauge transverse separation.

The equations for determining the local bending strains, the maximum bending strain, and percent bending are the same as given above for thick rectangular alignment cells but with substituting ε_1, ε_2, ε_3 and ε_4 by ε_{1e}, ε_{2e}, ε_{3e} and ε_{4e}.

6 DETERMINATION OF THE SEPARATE BENDING CONTRIBUTIONS

The contribution due to the test machine's misalignment to the total bending measured on the alignment cell surface can be evaluated by subjecting the alignment cell to an axial load in one orientation and recording the strain gauge readings, and by repeating this after rotating the alignment cell 180° about its vertical axis. By rotating the alignment cell, its bending contribution rotates relative to the machine while the machine's bending component remains stationary. The machine's contribution corresponds to one half of the difference between the local bending strains. Averaging the bending strains for any single gauge at two diametrically opposite positions results in the bending component at the location of that gauge due to inherent imperfections in the strain-gauged specimen or alignment cell.

For example, at Gauge 1, the local bending strain component due to the machine is:

$$b_{1.mc} = \frac{b_1(O_1) - b_1(O_2)}{2} \tag{17}$$

and the local bending strain component due to the specimen is:

$$b_{1.sp} = \frac{b_1(O_1) + b_1(O_2)}{2} \tag{18}$$

where $b_1(O_1)$ and $b_1(O_2)$ are the local bending strains measured by Gauge 1 when located in Orientation 1 and Orientation 2, respectively.

An alternative and more systematic evaluation procedure that can be used with cylindrical alignment cells is to take readings in all four orientations shown in Figure 2. In this case the local machine bending contribution can be calculated from the averages of the local strain readings of the four gauges when they are located at the same position with regard to the machine frame. For example, the local bending strain at Gauge 1 is:

$$b_{1.mc} = \frac{b_1(O_1) + b_3(O_2) + b_4(O_3) + b_2(O_4)}{4} \qquad (19)$$

The maximum bending strain, $b_{max.mc}$, is calculated by substituting the local bending strains, b_{mc}, values resulting from equation 17 or 19 into equation 6 for cylindrical alignment cells or equation 12 for rectangular alignment cells. The percent bending, β_{mc}, is then calculated from equation 11.

7 ALIGNMENT CLASSIFICATION

The level of the machine alignment may be described according to the criteria specified in Table 3 below and shown graphically in Figure 5.

Table 3. Alignment classes

Class	Abs (a) < 1000 με	Abs (a) ≥ 1000 με
2	$b_{max.mc} \leq$ 20 micro-strain	$\beta_{mc} \leq 2$ %
5	$b_{max.mc} \leq$ 50 micro-strain	$\beta_{mc} \leq 5$ %
10	$b_{max.mc} \leq$ 100 micro-strain	$\beta_{mc} \leq 10$ %
20	$b_{max.mc} \leq$ 200 micro-strain	$\beta_{max} \leq 20$ %

8 PROCEDURE FOR THE VERIFICATION OF MACHINE ALIGNMENT

8.1 Purpose of verification

The purpose of the present verification procedure is to demonstrate that the grip interface and load train couplings are in an alignment condition such that the test system consistently meets the requirements of the test standard. This procedure should be incorporated within the overall maintenance strategy of the test system. It is good practice that the same alignment cell is used for successive alignment verifications.

8.2 Frequency of measurement

This procedure should be carried out as frequent as is deemed necessary to ensure that the machine alignment is maintained and, as a minimum, when one or more of the following conditions apply:

1) Immediately after force calibration.

2) The load train has been repaired or disassembled and reassembled.

3) The machine's cross-head is moved, unless it has already been demonstrated that such movements do not affect alignment.

Good practice requires a high degree of confidence that the measurement is meaningful and repeatable and that the machine alignment is maintained. This normally need only be established once by performing 10 or more successive bending measurements in one orientation.

8.3 Procedure

1. Carry out any necessary preliminary adjustments using appropriate means to reduce any misalignment in the machine's load train.

2. Connect the lead wires of the strain gauges to the conditioning equipment and allow the system to equilibrate under power for at least 30 minutes prior to making any readings.

3. Mount one end of the alignment cell in the grip interface so that gauges A1 to A4 are located in the upper plane and the alignment cell is in the Orientation 1 position.

4. Zero the strain gauges.

5. Mount the other end of the cell in the grip interface, and with the machine at zero force or zero axial strain, as desired, record the strain gauge readings.

6. Apply steady tensile and or compressive forces, as appropriate, to achieve, at least, a total of seven predetermined successive levels of axial force, *F*, or axial mean strain, *a*. At each step, record the corresponding force and the strain gauge readings.

7. Different schemes of force or strain levels are given below for demonstration:

   F = 0, +5, +10, +15, +20, +25, +30, -5, -10, -15, -20, -25, -30, 0 kN
   F = 0, 5, 10, 15, 20, 25, 30, 0 kN (in tension or compression, as relevant)
   a = 0, +500, +1000, +1500, +2000, -500, -1000, -1500, -2000, 0 micro-strain

a = 0, 500, 1000, 1500, 2000, 2500, 0 micro-strain (in tension or compression, as relevant)

Note: The highest force or axial strain applied to the alignment cell must not exceed 0.5 of its proportional limit to avoid permanent damage.

8. Disassemble and reassemble the components of the load train including taking the alignment cell completely out of the grips, then repeat steps 3 to 7 after rotating the alignment cell 180° about its longitudinal axis. For a more systematic and robust study of the effects of rotational positions of components of the load train, a total of four measurement runs should be performed at 0°, 180°, 90° and 270°.

9. Calculate the values of maximum bending strain and percent bending and determine the alignment class. Specific alignment requirements should be dictated only by the relevant test standard or by a customer demand.

10. To evaluate the repeatability of the measurement repeat steps 3 to 8 ten times or more in one orientation. For a mechanically stable, well-aligned system, the determined maximum bending strain values should be repeatable to within ± 20 micro-strain. This step is usually needed once in order to characterise the alignment performance of the load train.

9 REPORTING OF RESULTS

9.1 Basic information

The measurement report should include the following:

1. Reference to this Guide;
2. Type and identification number of the test machine;
3. Description of the alignment cell used in the verification including its material, the dimensions of the reduced section and the identification number;
4. A schematic drawing showing the numbering and the locations of strain gauges;
5. Name of manufacturer of the strain gauge, the manufacturer's designation, strain gauge resistance, strain gauge factor, adhesive and coating used;
6. Type and identification number of strain measuring equipment, maximum error of the equipment, and the date of any calibrations;
7. All strain and force readings taken during verification;
8. The Alignment Class
9. The name of the operator and the date of verification.

9.2 Special information

Any deviations from the procedure given above should be stated with details.

ACKNOWLEDGEMENTS

The work described here was part of the EC/VAMAS collaborative project: *'Quantifying Data Uncertainties and the Validation of a Code of Practice for the Measurements of Bending in Uniaxial Fatigue Test Pieces'*, which was partly funded by the Commission of European Communities through the Standards, Measurement and Testing Programme, Project MAT1-CT94-0079. The author gratefully acknowledges the invaluable contributions made by his European and VAMAS Partners. Many thanks are also due to Dr Carlos Saraiva-Martins for his continued guidance and encouragement and for approving this publication.

The author is indebted to both Mr Terry Gorley for reading the manuscript and Miss Pamela Jones for preparing the graphics.

This report was produced with support from the UK Department of Trade and Industry as part of a programme of underpinning research on materials measurements.

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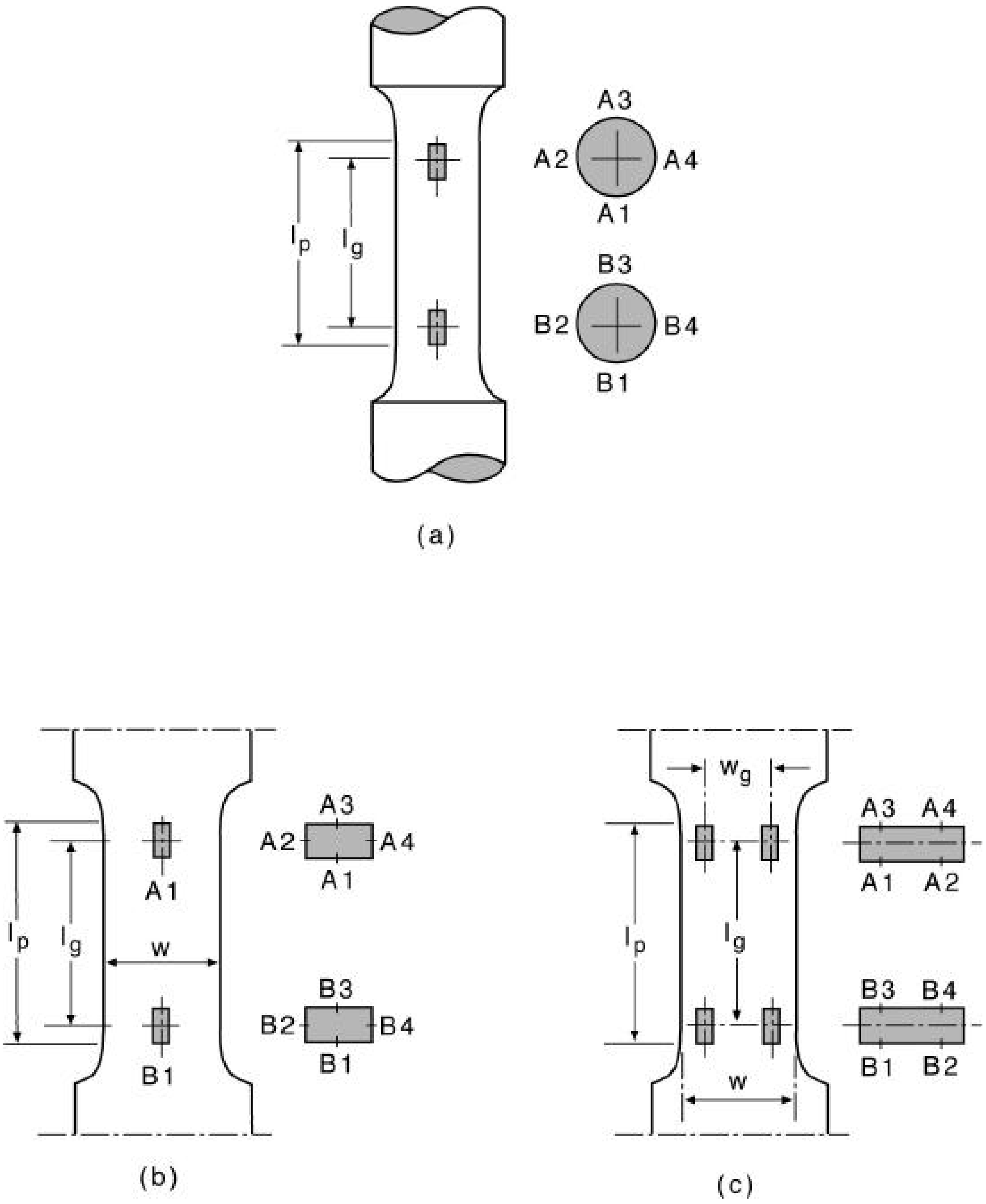

Figure 1. Strain gauge locations for alignment cells (a) cylindrical (b) thick rectangular and (c) thin rectangular

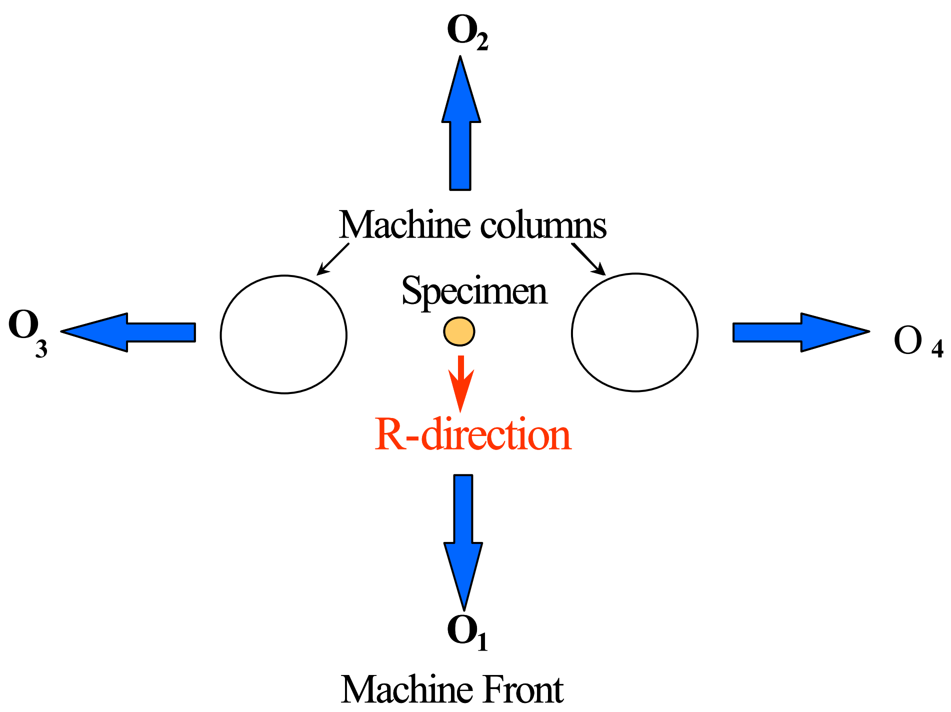

Figure 2. Definitions of the R-direction and the specimen orientations used in alignment and bending measurements (top view)

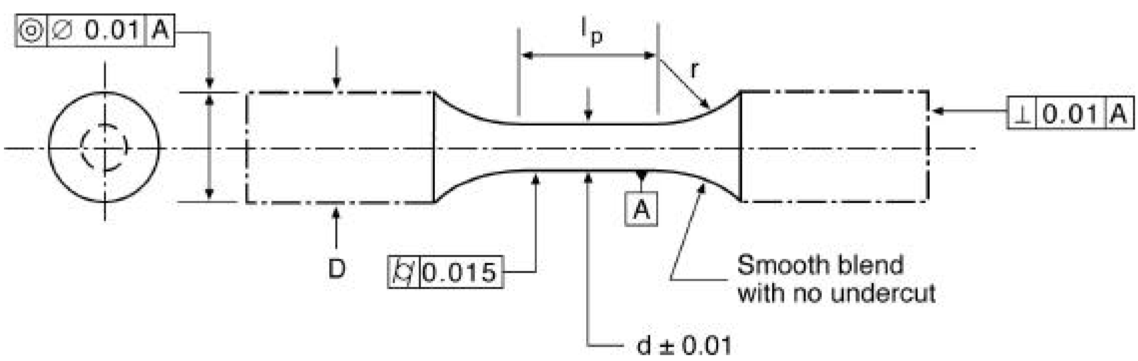

Figure 3. Profile for a cylindrical alignment cell

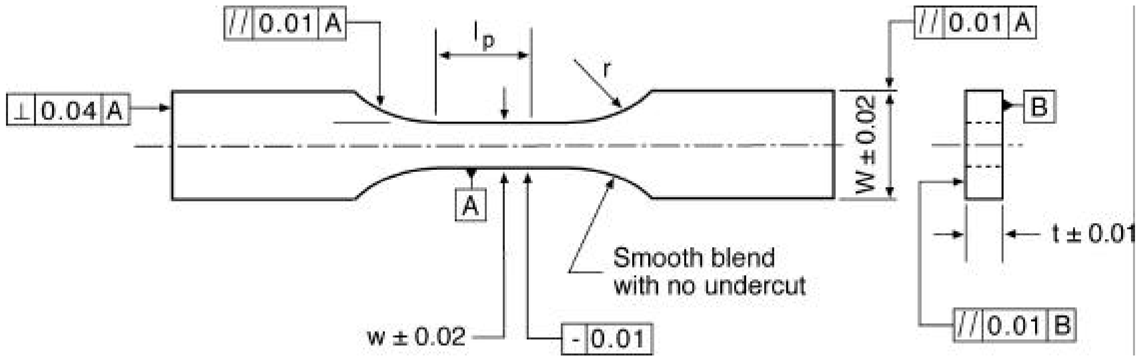

Figure 4. Profile for a rectangular alignment cell

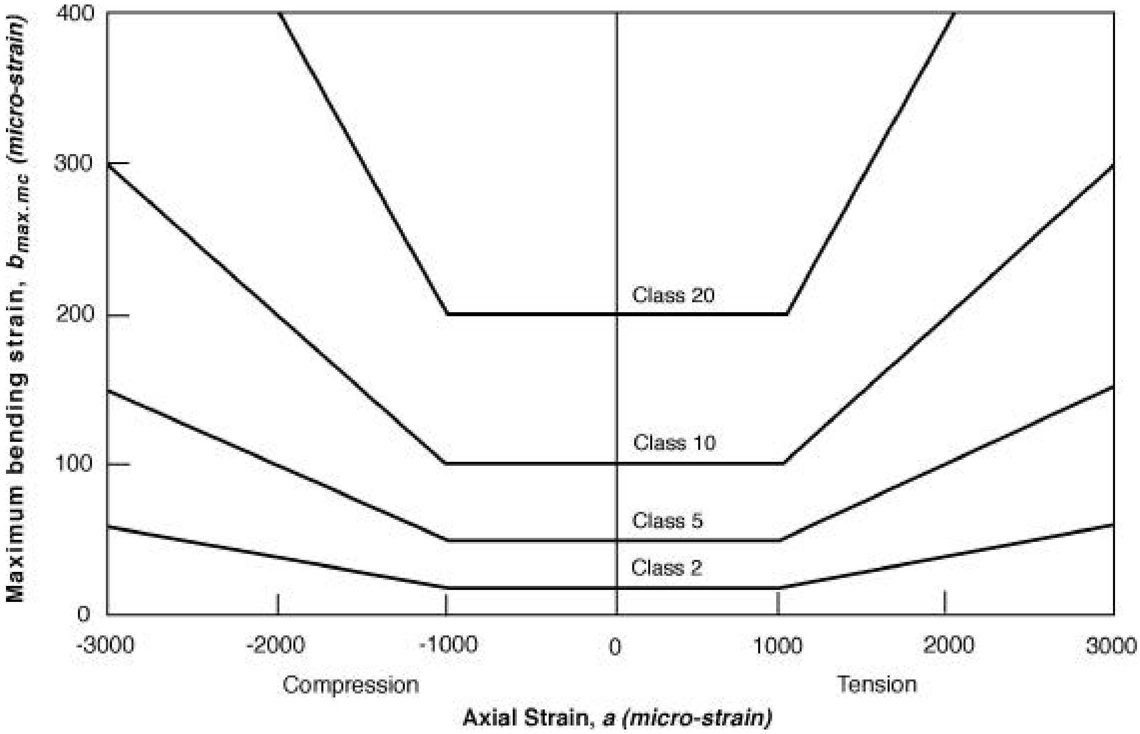

Figure 5. Criteria for Alignment Classification