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Compressive Testing of Ductile High-Strength Alloys

Reference

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ABSTRACT

Compression testing of metal alloys is a basic procedure in material characterization and analysis. Though it follows many of the guidelines and physical considerations as tensile testing, in some respects compression testing implies more complexity, more difficulties, and, consequently, more possible causes for inaccuracy compared to tensile testing. Hence, compressive testing is applied much less than the standard tensile tests, unless the load case is requiring specific test data from compression, e.g., when brittle or cast alloys are applied. Ductile metals compressed to high strains require further consideration when the yield strength in compression, the compressive strength, or even the full flow curve for plasticity must be identified. A sophisticated test procedure for compression testing of ductile metals in the plasticity range has been developed and is presented. It allows the determination of elastic modulus, yield strength, and flow curve up to high strains. The procedure was evaluated with comparative tensile tests on identical specimens and with a round-robin test with a testing-machine manufacturer. Further considerations for compression testing and for the strain measurement are presented.

Keywords

compression testing, yield strength, strain measurement, Young's modulus, flow curve

Introduction

Many basic material parameters of brittle and ductile materials are determined by means of static tensile testing, i.e., the elastic or Young's modulus, the yield strength, the ultimate tensile strength, and, finally, the flow curve for ductile metals. Most of these parameters should result in

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identical values when measured either in a tensile or in a compression test. However, as soon as plasticity comes into play, this statement is no longer true. The measured nominal or engineering stress-versus-strain curves have to be converted to true or local stresses to provide comparable values, and the elongation at break (or ultimate strain at break) depends on the local necking in the tensile test, which does not occur in the compression test. But as the critical load cases and also the failure mode 1 in fracture mechanics involves tension, the results from uniaxial tensile tests are usually convenient and sufficient for adequately describing a material's characteristic and performance. Consequently, there exist many well-established and validated standards for tensile testing, which shall not be further considered in this paper. For compression testing, there also exist several standards that are mainly adapted for brittle materials, such as cast iron, concrete, or ceramics. These standards are partly quite old and certainly proven and well approved; nonetheless, they do not address all the difficulties related with the test procedure, nor do they address all the parameters to be considered depending on the type of result required.

The German standard DIN 50106 [1], e.g., is originally from 1960 and was revised in 1978. It was mainly written for the determination of the compressive strength of brittle (cast) alloys, and it says very little about the allowable type of strain or displacement measurement. The standard is not particularly designed for the measurement of Young's modulus or yield strength.

ASTM E9-09 [2] describes, in particular, the adequate test setup with respect to axial alignment and parallelism of the two hardened bearing blocks, and it addresses the problems related with buckling of slender test samples and "barreling" (the non-uniform deformation in the sample's end region caused by friction). The standard refers to ASTM E111-04 [3] for the accurate determination of the Young's modulus where, in addition, a possible directionality is mentioned, i.e., a possible asymmetry of the material stiffness depending on the stress state (tension or compression). This can be one rationale to perform compression tests following the procedure presented in this paper. In compliance with ASTM E9-09 and E111-04,

extensometers are intended for the strain measurements that have to fulfill the practice of ASTM E83-10a [4]. Electrical resistance strain gauges are mentioned as one possible and allowed alternative in ASTM E9-09, where the method has to comply with ASTM E251 [5]. However, the type of caliper or extensometer for compression tests is ultimately not recommended or even restricted by ASTM standards. The speed of testing, i.e., the strain rate, is identified as another critical test parameter in ASTM E9-09. The standard explicitly describes the calculation and evaluation of the modulus of elasticity and the yield strength.

Depending on the type of material to be tested, a wide range of sample geometries is suggested. Most of the samples have a cylindrical geometry with planar, polished faces, but with varying aspect ratios h/d_0 , which are summarized in **Table 1**.

When the present test procedure was developed, the focus was on the accurate determination of the flow curve of ductile high-strength metal materials, i.e., on the total stress-strain relationship above the yield strength of such alloys. If possible, the procedure should simultaneously allow the determination of the elastic modulus and the yield strength of the tested materials, which also allows the comparison to results of tensile tests and, thus, the verification of the validity and accuracy of the procedure.

The yielding properties and the Young's modulus of ductile metals can depend on the direction of loading, i.e., they can show a directionality. The anisotropy or directionality can originate from microstructural changes, such as the formation of twin crystals under certain load states [6–8], or the formation of secondary martensite in austenitic steels (also δ -ferrite, cf. Refs 9 and 10), which is an undesirable effect, e.g., with biomedical grade 316L stainless steels. If the yield curves of an alloy are not congruent in tension and compression, it is feasible to determine the yield curve for a loading situation that will correspond to the load case of the component to be designed. In the present case, finite-element simulations had to be performed with load cases dominantly in compression (e.g., microindentation); thus, a yield curve from compression tests promised more accurate results than a yield curve from tensile tests.

TABLE 1 Allowable h/d_0 aspect ratios for cylindrical specimen according to different standards.

Standard	ASTM E9-09	DIN 50106	ISO 4385 (UNI 558, 1985)	ISO 13314
Scope/Range of Application	Metallic Materials	Brittle (Cast) Alloys	Metallic Bearing Materials	(Ductile) Porous and Cellular Metals
Allowable range of h/d_0 ratios	0.8–10	1–2	1.0	1–2
"Short": for bearing materials	0.8–2.0	1.0	1.0	
"Medium": for general compressive strength properties of metallic materials	3.0			
"Long": for elastic modulus determined	8–10			
High-strength materials	1.5–2.0	1.5		

FIG. 1

Displacement measurement with two calipers on the lower bearing block (arranged opposite to the specimen with averaged measurement values) leading to unsatisfactory results.

Materials and Methods

DEVELOPMENT OF TEST PROCEDURE

Strain Measurement

A first approach for the strain measurement of the compressed sample consisted of a measurement of the gap between the two hardened bearing blocks as in **Fig. 1**. The setup was in accordance with **Fig. 4** in ASTM E9-09 [2]. The two hardened bearing blocks had been aligned in parallel before the test start by means of a spherical calotte. The measurement was performed with the averaged signal of two calipers, which were arranged diagonally opposite of the specimen (to correct further misalignment during the test). The measurement is directly performed at the sample and suppresses the recording of any deformation in the test rig during the increase of the test load. If the measurement was performed by means of cross bar displacement, a previous correction curve should be measured without any test sample mounted, so that the test rig deformation can be subtracted from the displacements recorded. But even with the averaged measurement directly at the sample, it quickly turned out that the accuracy of the evaluated Young's modulus was not in the desired and expected order.

Therefore a second approach for strain measurement was chosen: A clip-on gauge from MF Mess- & Feinwerktechnik GmbH (type "Mini MFA 2") was directly applied to the test cylinder. It measures on two opposite sides of the sample with an initial measurement length of $l_0 = 10$ mm, and also provides an averaged signal. The measurement is based on strain gauges placed inside a mechanism, which is activated by two blades placed on the sample. A drawback is the maximum strain of approximately 10 % that can be measured, and it requires more space between the bearing blocks than the chosen sample length of 15 mm. The samples, thus, had to be placed between two hardened cones made of DIN 1.3351 [11]. A detail of the strain

measurement is shown in **Fig. 2**, with the clip-on gauge approx. mounted at mid height of the sample.

To get the full curve of plasticity, a specially developed test procedure for this type of displacement gauge was applied. The test procedure is implemented in the testing machine Zwick (type 1494, maximum load 600 kN) and based on the test software testXpert II. The evaluation of nominal strain starts directly with the clip-on gauge signal. After reaching a set strain value of >2 % (in the present case ~ 4 %, i.e., far above the yield strength of any alloy), the recording of the nominal strain switched to the cross bar displacement, where only the increment of displacement was needed. Thus, all of the internal deformation of the test machine was already excluded in the signal used after 4 % nominal strain, as this additional deformation mainly happens during load increase, but, after 4 % strain, the load level remains on the same order of magnitude. If only the cross bar displacement was used for the strain calculation, a correction curve would have been required, which allows subtraction of the internal machine deformation (usually recorded antecedent by loading the test rig without sample). The final procedure used is shown schematically in **Fig. 3**.

FIG. 2 Detail of the mounted clip-on gauge on a cylindrical test sample.

FIG. 3 Schematic description of the strain measurement based on two different inputs.

Mechanical Setup

A setup was chosen, where the two hardened and polished bearing block surfaces can be set to parallel under preload by means of a spherical calotte. It was an important requirement to fix the block's surface orientation after reaching the preload such that the calotte cannot further rotate under increased load. Two hardened cones were used to increase the working space between the parallel bearing block surfaces such that the clip-on gauge could be placed on the specimen after the cylindrical sample had been aligned in the machine axis and set under preload (cone material: DIN 1.3351 or HS6-5-4' according to BS EN ISO 4957 (12/1999), hardened to a Rockwell hardness ≥ 65 HRC). The chosen setup is shown schematically in **Fig. 4**.

MATERIALS AND VALIDATION TESTS

The material for the development of the procedure and the validation against tensile tests was a grade AISI 316L stainless steel (DIN 1.4441, implant quality), with further specifications as follows: X2CrNiMo 18-15-3 (ISO 5832-1, UNS S31673, ASTM F138), tensile strength between 930 and 1100 MPa. All samples

were produced from the same batch of a polished rod with circular cross section (diameter $\varnothing = 10.00$ mm; tolerance $h6$, i.e., $+0/-9 \mu\text{m}$). Out of this rod, the following test samples were manufactured for a round-robin test:

- Tensile test: according to DIN 50125 (type "F 10 $\times$ 50") with rod length 500 mm (Empa) and 330 mm (external laboratory), respectively.
- Compressive test: on the basis of DIN 50106 and ASTM E9-09 with cylindrical shape (diameter $d_0 = 10$ mm) and $h = 15$ mm, which results in an h/d_0 ratio of 1.5.

The advantage of using the polished rod was mainly that no further machining of the outer cylindrical surface was required, and no dimensional difference between tension and compression was introduced. If any granular variations or a radial inhomogeneity (gradient concerning grain size, phases) should be present in the rods because of mechanical and thermal treatment, a change in diameter from tensile sample to compressive would lead to an altered overall behavior in the phase of yielding or plastic deformation.

The tensile test was then performed according to DIN EN ISO 6892-1, where the strains were measured with a transducer type multiXtens from Zwick (class 0.5 according to EN ISO 9513). The compressive test was consequently following the procedure developed in this study, i.e., on the basis of DIN 50106 and ASTM E9-09. A comparative round-robin test was performed in an external lab for validation (manufacturer of testing machines) according to the same specifications, and identical samples were provided from Empa.

The strain rates were adjusted carefully considering the limits given in DIN EN ISO 6892-1, such that the strain rate in the elastic domain for tension was similar to the rate in the elastic domain for compression. The strain rates during plastic deformation were set higher by an order of magnitude, but again comparable for tension and compression.

FIG. 4

Schematic view of the mechanical setup (left) and installation with a prepared sample in the test machine (right; with large plates adjusted in parallel).

FIG. 5
 Typical results of a tensile and a compressive test comparison (Empa test results).

Results

The results are only presented for the test setup according to Fig. 4, as the results for the setup shown in Fig. 1 were unsatisfactory. The reason for that will be explained in the discussion section. Two exemplary test results in tension and compression from Empa are shown as plots of nominal stress versus nominal strain in Fig. 5. It is evident that, in the elastic domain, both curves follow each other up to the yielding point, and then they diverge because of geometrical effects. The tensile sample gets more slender, and the compressive sample broadens. The results of the round-robin test are shown in Table 2.

The results for Young’s modulus E and yield stress $R_{p0.2}$ are very comparable between tension and compression when looking at the results from Empa, although the evaluation of these parameters happens in the initial steep section of the curve, where small errors in the strain measurement lead to high errors for the calculated material parameters. The Young’s

modulus in tension identified by the external laboratory is just in between the values from Empa. However, the elastic modulus in compression drops considerably compared to the three other values. The same can be observed for the yield strength $R_{p0.2}$. The values from Empa in tension and compression match well with the tensile results from the external laboratory, whereas the external compressive result exceeds the average value from Empa by 6.3 %. The difference in ultimate tensile strength R_m between Empa and the external laboratory indicates a certain disparity in the calibration of the load cell, as this value does not depend on the strain measurement.

Discussion and Conclusions

During the development of the test procedure, one major finding was the fact that the parallelism of the two grinded surfaces of the bearing blocks must be adjusted in advance of the test or just during the application of the preload, and then the surface

TABLE 2 Overview and comparison of the results from the round-robin test.

	Empa			External Laboratory		
	Tension	Compression	Compression/Tensions	Tension	Compression	Compression/Tensions
Young’s modulus (MPa)	178 714	174 371	−2.43 %	175 818	151 363	−13.9 %
Rp0.2 (MPa)	778.7	777.3	−0.18 %	786.3	826.8	5.15 %
Rp2.0 (MPa)		970.3			988.5	
Rm (MPa)	970.7			983.7		
n (No. of samples)	3	4		3	3	

with its bias must be fixed. This parallelism is only of importance at the beginning of the test in the elastic domain of the test curve, and mainly influences the determination of the modulus of elasticity. As soon as the sample yields, an initial small error in parallelism will be suppressed. Any calotte for the correction of parallelism has to be blocked before the yield stress of the sample is reached, either because of the internal friction or with a mechanical stop. All spherical calottes and ball-and-socket joints, as per **Fig. 5** in ASTM E9-09 [2], act as hinges, and together with the yielding sample, which likewise acts as a plastic hinge, an instability and, hence, a lateral movement of a bearing block or the sample itself is inevitable.

If the yield curve of the tested material is required, an aspect ratio h/d_0 of 1.5 to 2.0 is adequate and fulfils the requirements of most of the standards. If the tests are conducted on high-strength materials, the sample diameter is also limited by the test machine capacity (or stiffness), which in the present study was in the range of 150 kN because of the machine compliance (approximately 120 kN maximum compressive load on the samples). These two aspects lead to the rather small sample dimensions of $\varnothing \times h = 10 \times 15$ mm, which made the samples difficult to handle. Slender samples with $h/d_0 > 3.0$ seem less adequate for testing in plasticity because of the mentioned stability problems. They are solely suggested for the measurement of Young's modulus.

One aspect at least as important as the parallelism of the bearing blocks is the lateral stiffness of the test machine. The compliance of the upper bearing block with respect to the lower block shall be minimized transverse to the loading direction. In the present study, no custom-built compression machine was available. The test had to be performed on a test machine designed for tensile testing, with some large hydraulic grips still mounted in the machine. The grips could not be removed because of repeatedly required calibration. The setup is shown in **Fig. 6** (left), and it is evident that the vertical distance from upper cross bar to the testing room (i.e., sample location) exceeds a reasonable measure. Furthermore, the coupling between load cell and upper grip has a reduced diameter and can act as an elastic hinge, which increases the lateral compliance of the upper test adapters. As a consequence, a lateral shearing or drift of the sample could be observed in some badly aligned experiments, besides the expected barreling (**Fig. 6**, top right). This may result in an explicit orientation of the shear bands during yielding; the slip planes in **Fig. 6** (bottom right, black dashed lines) with their normal vectors n will orient under a specific angle φ with respect to the vertical test axis (Z) instead of being equally distributed in circumferential direction. Under a tensile load, the slipping will always occur equally distributed over the full 360° of a round tensile sample, and thus, the necking will happen in an axisymmetric manner. Although the

FIG. 6

Mechanical setup in the tension testing machine (*left*), lateral drifting of upper cone during yielding (*right top*), and explicit orientation of shear bands in the flowing material (*right bottom*).

phenomenon of lateral drift could be observed, no clear influence on the start of yielding and, hence, the yield strength, could be established. Nonetheless, the authors recommend specifically designed compression testing machines to perform compressive tests on high-strength materials. The machines should be designed compact with preferably four columns instead of two and a stiff lateral guiding rail for the compression plates (for example, similar to machines for concrete testing).

Many authors and standards point to the aspect of friction between compression test samples and bearing blocks, which leads to the barrel-like deformation of the samples. Friction effects were also scrutinized at the beginning of this study. An axisymmetric finite-element model (FE model) was built to simulate the compression test with all parameters set to match the real experiment. The friction coefficient in the model was varied from $\mu=0$ (no friction) to $\mu=0.4$. The surprising results showed no dominant effect of friction if the strains in the model were evaluated in the same way as the clip-on gauge performs the measurement in the tests. The change in vertical distance of two surface nodes with an initial gap of 10 mm was recorded and the nominal strain was calculated. **Figure 7** shows two deformed models with and without friction (FE results for

magnitude of displacement and equivalent plastic strain, respectively), and **Fig. 8** the resulting plot of nominal stresses versus nominal strains. No significant variation up to 20 % strain can be observed.

The FE results presume that the material behaves isotropically and is homogenous over the full process of plasticizing, as changes in the microstructure or the development of predominant directions in the grains or shear bands cannot be reproduced. **Figure 2** in ASTM E9-09, however, indicates that the microstructure gets aligned depending on the magnitude of friction. Therefore, the differences between good lubrication (no friction) and high friction may be higher in reality.

The strain measurement was an open issue at the beginning of the project. It quickly turned out that the measurement had to be done locally on the sample, either by means of glued strain gauges or by means of the finally used clip-on gauge, which internally also operates with strain gauges, but measures initially a displacement between two points. The applied gauge had an initial measurement length of 10 mm, and a maximum displacement of 4 mm. The early attempts with a layout according to **Fig. 1** led to wrong results for this high-strength material. If the modulus of elasticity of the tested material is of the same order

FIG. 7
Axisymmetric FE model of a compression test ($u_{Ymax} = -4.0$ mm), left: without friction, right: with friction $\mu = 0.1$.

FIG. 8

Plot of nominal stress versus strain for four different friction values for a comparable 316L alloy.

as the elasticity of the (hardened, flat, polished) bearing blocks, then the elastic imprint of the test sample leads to additional displacements measured by the calipers, so that, finally, the accuracy for an evaluation of the Young's modulus is insufficient. This circumstance was finally proved with an extended FE model of the actually used base bearing plate, which additionally has a 3-point support, cf. **Fig. 9** (symmetric half-model).

FIG. 9 FE results of the elastic imprint in the base bearing block.

Taking into account the upper bearing, the additional displacement measured because of the elastic imprint is easily in the range of 0.1 mm for a normalized stress of 1000 MPa.

Therefore, it is recommended to use a configuration as in **Fig. 1** only for low modulus materials such as plastics, rubber-like materials, or composites, where the Young's modulus is 100 to 1000-times smaller than the one of hardened steel. Any high modulus materials require a local strain measurement directly on the compression sample, if the Young's modulus and the yield strength are of major interest. Furthermore, at least two measurements on each sample are necessary in a diagonal arrangement (180° opposite location on the cylindrical sample), such that the values may be averaged (will suppress any contribution because of bending stresses).

It can be concluded that the established standards were most probably designed only for specific measurements of individual material parameters: ISO 50106, e.g., for the measurement of the compressive strength of brittle materials; and ASTM E9-09, additionally for the measurement of yield strength or Young's modulus (in consideration of ASTM E111-04). But none of them seems directly applicable for the identification of the yield curve of ductile alloys. The flow curve of ductile materials can be assessed by compression testing, if some aspects presented in this study in addition to the recommendations in common standards are considered.

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