New Approach of Metals Ductility in Tensile Test

Badreddine R1*, Abderrazak D2 and Kheireddine S2

1Departement de métallurgie et génie des matériaux, laboratoire de métallurgie et génie des matériaux, université badji mokhtar 23000 Annaba
2Research Center in Industrial Technologies, CRTI P. O. Box 64, Cheraga 16014 Algiers, Algeria

Abstract

Ductility is the ability of a material to deform plastically before rupture. This is an important feature in shaping because it helps to define the behavior of materials. Ductility is therefore essential to know and thus determine to anticipate the behavior of materials in various situations of stress. Ductility is commonly defined by the two parameters A elongation (in percent) or necking Z (in percent) with:

\[ A(\%) = \Delta L / L_0(\%) = (L_1-L_0) / L_0(\%) \]
\[ Z(\%) = \Delta S / S_0(\%) = (S_0-S_1) / S_0(\%) \]

These two parameters are determined from tensile tests on standard specimens.

We will focus on the study and analysis of ductility using the tensile test.

However these two indicators (A) and (Z) of the ductility may present deficiencies (contradictions) in the interpretation of the ductility in case where for two samples (1) and (2) with same original dimensions (Lo) and (So) and different composition we could have: \( A_1 > A_2 \) and \( Z_1 < Z_2 \) or \( A_1 < A_2 \) and \( Z_1 > Z_2 \).

These two cases show the anomaly between A and Z in the assessment of the ductility, in fact in the first case the sample (1) is more ductile than the sample (2) in terms of elongation (A) is less ductile necking in terms of (Z) against the 2nd case we find the opposite behavior; it is this inconsistency that we will approach the ductility by introducing a parameter which will be called ductility (D) which takes into account the elongation and necking in a single formulation. In fact, (D) could remedy this deficiency involving computational approaches by activating the settings of the length (L) and Section (S) across the diameter (d) together in a first approach and to other computational approaches that take into account the elongation A and the neck.

Keywords: Ductility; Elongation; Necking; Tensile; Approach

Introduction

Ductility is the ability of a material to deform plastically before rupture. This is an important feature in shaping because it helps to define the behavior of materials. Ductility is therefore essential to know and thus determine to anticipate the behavior of materials in various situations of stress. Ductility is commonly defined by the two parameters A elongation (in percent) or necking Z (in percent) with:

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However these two indicators (A) and (Z) of the ductility may present deficiencies (contradictions) in the interpretation of the ductility in case where for two samples (1) and (2) with same original dimensions (Lo) and (So) and different composition we could have:

\[ A_1 > A_2 \] and \( Z_1 < Z_2 \)

Or \( A_1 < A_2 \) and \( Z_1 > Z_2 \)

These two cases show the anomaly between A and Z in the assessment of the ductility, in fact in the first case the sample (1) is more ductile than the sample (2) in terms of elongation (A) and less ductile in terms of necking (Z), in the 2nd case we find the opposite behavior; it is this inconsistency that we will approach the ductility by introducing a parameter which will be called ductility (D) which takes into account the elongation and necking in a single formulation. In fact, (D) could remedy this deficiency involving computational approaches by activating the settings of the length (L) and Section (S) across the diameter (d) together [1-20].

Materials and Methods

Ductility modeling and approaches of metals

Highlighting the contradiction of the ductility value between the parameters A(%) and Z(%): The anomaly of appreciation of ductility that we expose, concerned the contradiction between the percent elongation parameter A(%), and the percent necking Z parameter (%). This anomaly is confirmed by numerous examples; among metals and alloys defined according to the American standard AISI and ASTM Table 1, some of them confirmed the contradiction between A(%) and Z(%) (Table 1) [21-40].

So this contradiction leads us to propose modeling approaches of ductility to remedy this inconsistency and thus give a more meaningful assessment of the ductility by inter reactive factors such as the length, section and through which the diameter during deformation (Table 2).

*Corresponding author: Badreddine R, Department de métallurgie et génie des matériaux, laboratoire de métallurgie et génie des matériaux, université badji mokhtar 23000 Annaba, Tel: +213 661 04 08 93; E-mail: bregalguia@yahoo.fr

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Uniform elongation is calculated by expressing the volume of the specimen between the landmarks of the test piece is not changed by this elongation, then:

$$\frac{d_0}{d_1} \times 100\%$$

(1)

Or: $d_0$ is the diameter of the specimen before the tensile test and $d_1$ after breaking.

$b(\%)$: lengthening of necking, established by the difference:

$$b(\%) = A(\%) - a(\%)$$

(2)

$A(\%)$: Total elongation measured on standard test specimen.

Assuming that $A = A_k + A_l$

We focus on the study of uniform elongation and elongation of necking during the tensile deformation.

It discusses this approach by a geometric representation formulation of these parameters enabled.

We consider a standard tensile bar with respectively:

$L_0$ and $S_0$: the length and the section before tensile test.

$L_1$ and $S_1$: the length and the section after tensile test.

By analyzing necking area, it is noted that:

Longer necking which is $\Delta L_s$ is a line that develops in the direction of the loading axis.

Necking which is the ratio of $\Delta S$ and initial section $S_0$ is represented in our approach by the difference of initial diameter $d_0$ and diameter after breaking $d_1$.

In the work that follows, we will focus our approach on the specimen deformation area (Figure 1).

According to Figure 2, it is assumed that:

- The test piece is perfectly symmetrical on both sides of the longitudinal and transverse axes.
- After the tensile test piece halves of both sides with respect to the break line (necking) are symmetrical.
- The breaking line (necking) is mingled with the transverse axis.
- The variation of the section profile in the necked area is made along a straight right from the beginning of the necking to failure.
- We introduced the concept of necking bearing represented by the oblique line $EB$ represents the profile of the evolution of reduced diameter.
- We introduce the notion of necking angle ($\alpha$) which is the angle resulting from the intersection of the transverse confused with $BC$ and $EB$ bearing.
- We introduced the concept of 1/2 ductility triangle whose base is necking diameter and height is total elongation.
- We introduced the concept of 1/2 ductility angle $\beta$ formed by the intersection of the base of the triangle (diameter necking) and the hypotenuse $OC$.

### Table 1: Mechanical properties of some metals [57].

<table>
<thead>
<tr>
<th>Metals</th>
<th>E (Gpa)</th>
<th>Rp (Mpa)</th>
<th>Rm (Mpa)</th>
<th>A%</th>
<th>Z%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ductile Iron A536 (65-45-12)</td>
<td>159</td>
<td>334</td>
<td>448</td>
<td>15</td>
<td>19.8</td>
</tr>
<tr>
<td>Rolled AISI 1020</td>
<td>203</td>
<td>260</td>
<td>441</td>
<td>36</td>
<td>61</td>
</tr>
<tr>
<td>ASTM A514, T1</td>
<td>208</td>
<td>724</td>
<td>807</td>
<td>20</td>
<td>66</td>
</tr>
<tr>
<td>Ni Maraging Steel (250)</td>
<td>186</td>
<td>1791</td>
<td>1860</td>
<td>8</td>
<td>56</td>
</tr>
<tr>
<td>Aluminium 2024 –T4</td>
<td>3.1</td>
<td>303</td>
<td>476</td>
<td>20</td>
<td>35</td>
</tr>
</tbody>
</table>

### Table 2: Examples of metals with a contradiction between the ductility parameters A (%) and Z (%).

<table>
<thead>
<tr>
<th>Metals</th>
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<th>Z (%)</th>
</tr>
</thead>
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<tr>
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</tr>
</tbody>
</table>

**Approach 1: Geometric modeling approach ductility according to the elongation and diameter necking**

This is a standardized tensile specimen with respectively $L_0$, $S_0$, length and initial section $L_1$, and $S_1$, length and section after tensile test. It is known that the elongation consists of two separate elongations including one distributed almost uniformly over the entire length of the test piece, while the other is located at the point of necking [41,42].
We note in Figure 2 that we have:

04 geometric representations highlighting \( \frac{\Delta L_r}{2} \), \( \frac{\Delta L_s}{2} \) et \( \frac{\Delta d}{2} \).

Symmetrically, 02-02 relative to longitudinal and transverse axes.

However, we will focus our approach of calculating the approach \( D_1 \) on geometric representation of the left upper half specimen. In the Figure 2 we see the necking profile across the necking bearing EB that means we see the profile of the evolution of strain in term of elongation and diameter reduction necking \( d \) until the breaking [43-47].

**Calculation Method of \( D_1 \) Ductility Approach**

Either the diagram of portion 1(3);

Note from the geometry:

\( \frac{\Delta L_r}{2} \) is the uniform elongation of the portion 1.

\( \frac{\Delta L_s}{2} \) is the extension of the constriction portion 1.

With: \( \Delta L_t \) total elongation at necking.

\( \frac{\Delta d}{2} \) is the difference between initial and final diameter of the portion 1.

According to Figure 3 we have,

The point O:

\[ \frac{\Delta L_r}{2} = 0 \text{ et } \frac{\Delta d}{2} = 0 \]

With \( \frac{\Delta L_r}{2} \) : the total elongation of the portion 1 of the specimen and \( \Delta d \): \( \Delta d \) the variation of the diameter.

This is the initial state at time \( t = 0 \) before tensile test.

At point A: There, there’s uniform elongation but there is no necking as \( \Delta d = 0 \).

Consequently the total elongation of the portion 1 is: \( \frac{\Delta L_r}{2} = \frac{\Delta L_r}{2} \)

At point B:

We have uniform elongation and necking because there’s \( \Delta d \neq 0 \)

Consequently the total elongation of the portion 1 is:

\[ \frac{\Delta L_r}{2} = \frac{\Delta L_r}{2} + \frac{\Delta L_s}{2} \]

With: \( \frac{\Delta L_r}{2} \) et \( \frac{\Delta L_s}{2} \), respectively: uniform elongation and necking elongation.

We note already in Figure 2 that: the necking elongation \( \Delta L_s \) can be calculated as follows:

\[ tga = \frac{\Delta L_s}{\Delta d} = \frac{\Delta L_s}{\Delta d} \]  \hspace{1cm} (3)

The angle \( \beta \) is introduced between the transverse which coincides with the necking diameter and the slant segment passing through the point O and the end of the necking diameter in point C introducing the tangent of the angle \( \beta \):

\[ tg\beta = \frac{OB}{BC} = \frac{OB}{d_1} = \frac{OA + AB}{d_1} = \frac{\Delta L_r + \Delta L_s}{d_1} = \frac{\Delta L}{2d_1} \]

So \( tg\beta = \frac{\Delta L}{2d_1} \)  \hspace{1cm} (4)

Note that the \( \beta \) angle is between \( 0^\circ \) and \( 90^\circ \): \( 0^0 \leq OCB \leq 90^0 \)

\[ tg0^0 = 0 \text{ et } tg90^0 = \frac{1}{0} = \infty \]

Indeed \( 0^0 \) corresponds to the initial state before tensile test or the ductility of the material is zero.

At \( 90^0 \) is the condition for which the ductility of the material is infinite.

**Interpretation**

We note from Figure 4 that:

When \( \beta = 0^0 \) this means that the material is brittle because its ductility expressed \( tg\beta \) is zero.

When \( \beta = 90^0 \) (Figure 5), it means that the material is ideally plastic that is to say the material is infinitely superplastic because its ductility expressed by \( tg\beta \) approaches infinity.
We see that $\tan \beta$ is a credible indicator of ductility because it activates simultaneously the elongation $\Delta L$ and the final necking diameter $d_1$ (Figure 6).

This formulation is interesting because it is based on the values of the elongation $\Delta L$ and the final necking diameter $d_1$ which are essential variables in the determination of the ductility of a material.

Among others we note that conventional formulas of ductility represented by the percent elongation $A$ and the necking percent $Z$ are dependent on these $02$ values, in fact elongation percent $A$ is a function of only $\Delta L$ and necking $Z$ is a function of the necking section $S_1$ it means that $Z$ is a function of necking diameter $d_1$ [48-57].

We shall agree to say, therefore, that our approach of ductility through the tangent of the angle $\beta$ gives a better description of the state of ductility of material than conventional parameters $A$ and $Z$.

**Checking the formula of ductility approach $\tan \beta = \frac{\Delta L}{2d_1}$ of portion**

When $\tan \beta = 0$ this corresponds to $\beta = 0^\circ \Rightarrow \frac{\Delta L}{2d_1} = 0$
We deduce: $\Delta L = 0$ et $d_1 = d_0$
This is the case of a brittle material whose ductility is zero.

When $\tan \beta = \infty$ it corresponds to $\beta = 90^\circ \Rightarrow \frac{\Delta L}{2d_1} \rightarrow \infty$ we deduce: $\Delta L > 0$ et $d_1 > 0$.
This is the case of a ductile material with ideally infinite ductility it is concluded from our approach $\tan \beta = \frac{\Delta L}{2d_1}$ the ductility of superplastic metallic materials and plastic is between 0 and infinity.

We conclude $\tan \beta = \frac{\Delta L}{2d_1}$ may be representative of the ductility of any material.

To finalize our approach of ductility formula, we notice that $\tan \beta$ is representative of the ductility of the upper half of specimen (Figure 3).

Based on the assumptions mentioned above, the test specimen is perfectly symmetrical on both sides of the axes, thus to have the total ductility, it is appropriate to add the ductility of the lower half specimen (Figure 7) or multiply our parameter $\tan \beta = \frac{\Delta L}{2d_1}$ by 2.

So $D_1 = 2 \tan \beta = 2 \frac{\Delta L}{2d_1} = \frac{\Delta L}{d_1}$

With $\Delta L$: total elongation and $d_1$: necking diameter.

So we see that the total ductility triangle is isosceles shape, with basic $\Delta L$ and total height the extension of necking diameter $d_1$ (Figure 8).

We also note that the total angle of ductility is the angle $\gamma = 2\beta$.

We note that the ductility parameter approach $D_1 = \frac{\Delta L}{d_1}$ is an interesting and promising contribution in the interpretation of ductility. It has been confirmed by audits on 03 types of materials.
ductility parameter from a simple tensile test on the 1/2 upper specimen.

The ductility approach $D_1 = \frac{\Delta L}{d_1}$ effectively solves the problem of the contradiction between $A$ and $Z$ concerning quantification of ductility and that is the problem targeted by the work (Figure 9).

**Analysis of approach** $D_1 = \frac{\Delta L}{d_1}$ for ductile metallic materials

To simplify the geometric representation of the $D_1$, we preferably use approach for the upper 1/2 specimen (Figure 10) or lower 1/2 specimen; while noting that the geometric shape relative to $D_1$ approach is an isosceles triangle that is the sum of 02 right triangles (rectangle triangles) perfectly identical and symmetrical and having a common base the diameter of the specimen.

According to Figure 10a shows the evolution of our approach ductility parameter from a simple tensile test on the 1/2 upper specimen.

In Figure 10, $D_1$ approach parameter before the beginning of the tensile test is shown by the initial state $\Delta L = \Delta L = 0$; Indeed, the elongation is zero and $\Delta d = 0$ which implies $d_1 = d_0$.

In this case: $D_1 = \frac{\Delta L}{d_1} = \frac{\Delta L}{d_0} = 0$

This is the typical case of brittle materials whose ductility is zero.

Figure 10b represents the beginning of the test; we note that there is a linear deformation along the longitudinal axis therefore representing the homogeneous deformation of the uniform elongation of the specimen.

![Figure 9: Geometric evolution of $D_1$ approach parameter on a specimen in tensile test.](image)

The $D_1$ parameter in this case is based only on the uniform elongation because it is homogeneous deformation and the initial diameter $d_0$ because there is no necking.

$$D_1 = \frac{\Delta L_{11}}{d_0}$$

In Figure 10c the homogeneous deformation representing uniform elongation is more pronounced than the previous but still remains in the field of homogeneous deformation, the uniform elongation $\Delta L_1$ increased passing $\Delta L_2 > \Delta L_1$, therefore only the uniform elongation occurs in changing the quantization ductility because necking elongation is zero and the diameter $d_1 = d_0$.

What gives us the setting $D_1 = \frac{\Delta L_{22}}{d_0}$.

In Figure 10d we notice the onset of necking one enters the area of the heterogeneous deformation indeed it’s diameter reduction and lengthening necking. The total elongation in this case is the sum of 02 elongations: distributed elongation and elongation necking $\Delta L_{02}$ and the diameter $d_1$ which is less than $d_0$.

Note that the uniform elongation is constant and equals to $\Delta L_{12}$ because it is no longer homogeneous deformation.

Where: $D_1 = \frac{\Delta L_{22} + \Delta L_{12}}{d_1}$

In Figure 10e necking is more pronounced, as necking elongation and diameter reduction are enabled, there is a slight increase in the value of the necking elongation and a decrease of the diameter from $d_1$ to $d_2$; $d_2 < d_1$.

This increase is induced by the increase in the value of the diameter reduction, that we confirm through the formula that we presented $\Delta L = \Delta d \cdot \gamma a$.

Indeed when $\Delta d$ increases, $\Delta L_{12}$ also increases, which means $\Delta L_{12} > \Delta L_{11}$.

Therefore the approach of parameter $D_1$ becomes equal to: $D_1 = \frac{\Delta L_{22} + \Delta L_{12}}{d_2}$

According to Figure 10f the breaking phase we are witnessing is the end of the necking so necking elongation increases $\Delta L_{22} > \Delta L_{12}$ and necking diameter decreases with $d_2$, less than $d_1$.

So the approach parameter will be: $D_1 = \frac{\Delta L_{22} + \Delta L_{32}}{d_3}$

We note that in general the ductility parameter $D_1 = \frac{\Delta L}{d_1}$ is growing throughout the tensile test and interprets perfectly plastic behavior through its 02 variables that are elongation $\Delta L$ and necking diameter $d_1$.

**Ductility Triangle and Ductility Angle Concepts of Approach $D_1$**

It is a specimen of a material subjected to a simple tensile test. Changes in ductility through the $D_1$ setting approach has been described above, however we will try to study the evolution of ductility triangle through the various phases of tensile strain. Either the 1/2 upper specimen, the mapping of the ductility is proposed to be made through the triangle by the projection on the longitudinal axis in Figure 11 which gives us the following:...
It is seen (FIG II.11) that $D_1$ approach parameter relating to the 1/2 specimen changes according to a right triangle whose height characterizing the elongation increases at the expense of shrinkage of diameter.

This change in shape of the right triangle called ½ ductility triangle is expressed by the variation of angle of inclination $\beta$ called 1/2 ductility angle.

We also note from the Figure 11, that as $\beta$ increases, the ductility formulated by $D_1$ approach also increases and vice versa true.

Indeed it is clear that: $\beta_1 > \beta_2 > \beta_3 > \beta_4 > \beta_5$.

Therefore it is concluded that the ductility of approach $D_1 = \frac{\Delta L}{d_1}$ on the ½ specimen is geometrically represented by a variable right triangular $D_1$ and this parameter is a function of the ½ $\beta$ ductility angle whose value is only determining ductility relative to our approach.

Note that the parameter $D_1 = \frac{\Delta L}{d_1}$ is finally dimensionless.

For the entire test the geometric representation of the $D_1$ approach is as follows in Figure 12.

Note on Figure 13, the evolution of the isosceles triangle ductility characterizing $D_1$ approach; Indeed, starting from t=0 to the beginning of the homogeneous deformation ductility scales linearly along the axis of stress is the uniform elongation and to the onset of necking there is formation of a triangle isosceles which characterizes the heterogeneous deformation according to the approach $D_1$. This form of this triangle changes gradually as the tensile test is carried out until breaking of the specimen.

Finally we conclude that changes in the geometry of the $D_1$ approach operate generally as follows in the Figure 14.

Figure 14.1: No deformation, it is the initial state before tensile testing; ductility is confused to a point.

Figure 14.2: Homogeneous deformations, it is the phase of the distributed linear expansion, there is no ductility triangle.

Figures 14.3 - 14.5: Heterogeneous deformation, it is the phase of the emergence and evolution of ductility triangle according $D_1$ approach.

Figure 14.6: The ductility triangle coincides with the vertical and corresponds to an ideal state of ductility that does not exist in reality. It operates between other than the area of the isosceles triangle is equal to $\frac{hh}{2}$ that is the product of base of the triangle and its ½ height.

Therefore the area of the triangle ductility characterizing $D_1$ ductility approach is equal to $\frac{\Delta Lxd_1}{2}$.

Note that the parameter $D_1 = \frac{\Delta L}{d_1}$ is dimensionless.

Results and Discussion

To study and analyze the contradiction between the assessment parameters of ductility $A(\%)$ and $Z(\%)$ we used in our experiment iron annealed copper annealed. These (02) grades are delivered in rolled state by the precision machining company located in El-Hadjar (Annaba city).

The various test pieces in number (03) for each grade were tested in the tensile test; the different values that we identified (final length and final diameter), are used to calculate average $\Delta L$ and necking diameter for proving the contradiction.

For iron annealed, elongation is between 40 and 50, the constriction...
is 80 to 93, the hardness HRB is from 45 to 55 and its modulus of elasticity (Young) is 206000 MPa.

To develop and analyze the second step of our work, we experiment tensile test on 03 different grades of carbon steel. For each grade, we use 03 specimens. Test grades are XC18 carbon steel, XC38 and XC48. Ductility values of the above-mentioned steels is known because of the carbon content, in other words it is known that XC18 is more ductile than XC38 and XC48 because it contains less carbon, and XC38 is more ductile than XC48. Based on this fact we test the ductility approach and we have to prove this order of ductility values of XC18, XC38 and XC48 (Figure 15).

**Experimental study of the ductility annealed iron and annealed copper**

The tensile tests were performed on 03 samples of annealed iron and copper.

**Figure 15:** Specimen dimensions.

**Figure 16:** Tensile test curve of annealed iron.

**Figure 17:** Tensile test curve of annealed copper.

**Figure 18:** Geometric representation of the D₂ approach for annealing copper and annealed iron.

**Figure 19:** Tensile test curve of XC18.

**Figure 20:** Tensile test curve of XC38.

**Figure 21:** Tensile test curve of XC48.
Figure 22: Geometric representation of the $D_i$ approach for XC18, XC38 and XC48.

Figure 23: 1st case: $A_1 > A_2$ and $Z_1 > Z_2$.

Figure 24: 2nd case: $A_1 < A_2$ and $Z_1 < Z_2$.

Figure 25: 3rd case: $A_1 > A_2$ and $Z_1 < Z_2$.

Figure 26: The 3rd possibility is a particular case.

Figure 27: 4th case: $A_1 < A_2$ and $Z_1 > Z_2$.

Figure 28: 5th case: $A_1 = A_2$ and $Z_1 = Z_2$.

Table 3: Comparative $A, Z$ annealed iron and annealed copper.
Experimental study of the ductility of XC18, XC38 and XC48

It is shown in Tables 3-8.

General application of the approach, $D_1 = \frac{\Delta L}{d_1}$

In this case, we have 3 possibilities; most interesting are:

Possibility 1 and 2: $\frac{\Delta L}{d_1} > \frac{\Delta L}{d_2}$

The 3rd possibility is a particular case:

With $\Delta L_1 \neq \Delta L_2$ et $\Delta d_1 \neq \Delta d_2$, we obtain:

$$\frac{\Delta L_1}{d_1} = \frac{\Delta L_2}{d_2}$$

Conclusion

Through this approach, we notice that $D_1$ is a valid and credible general parameter because its formula takes into account the longitudinal deformations using $\Delta L$ and the transverse deformations and transverse deformation across the necking diameter $d_1$. On the other hand the geometric representation of $D_1$ is interesting because it schematizes the ductility of materials using ductility triangle and ductility angle that we have presented.

References

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