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# Ductility and plasticity of nanostructured metals: differences and issues

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ABSTRACT

Ductility is one of the most important mechanical properties for metallic structural materials. It is measured as the elongation to failure of a sample during standard uniaxial tensile tests. This is problematic and often leads to gross overestimation for nanostructured metals, for which non-standard small samples are typically used. Uniform elongation is a better measure of ductility for small samples because they are less sensitive to sample size. By definition, ductility can be considered as tensile plasticity, but it is often confused with plasticity. In principle, ductility is largely governed by strain hardening rate, which is in turn significantly affected by microstructure, whereas plasticity is primarily controlled by crystal structure or the number of available slip systems to accommodate plastic deformation. In practice, ductility is important for preventing catastrophic failure of structural components during service, whereas plasticity is critical for shaping and forming metals into desired shape and geometry to make structural components. Nanostructured metals typically have high plasticity, but low ductility, due to their low strain hardening capability. Increasing strain hardening rate via modifying microstructure is the primary route to improving ductility.

## 1. Introduction

Reasonable ductility (usually >5%, preferably >10%) is desired to prevent mechanical components or structures from catastrophic failure during service [1]. On the other hand, high strength is also desired so that a metallic structure/component can carry large load at low material weight. This is especially important for future transportation vehicles such as electrical cars, which need to be lightweight to improve their energy efficiency. However, a metallic material is either strong or ductile, but rarely both at the same time [2,3]. Coarse-grained (CG) metals usually have high ductility but low strength. Refining grains to the nanocrystalline regime in the last few decades has significantly increased strength, but this is often accompanied with the sacrifice of ductility [4]. The low ductility of nanostructured metals has been a major issue with their potential structural applications.

Ductility of nanostructured metals has been a hot research topic for over a decade [2–7]. However, despite the extensive research and publications, there still exist widespread confusions and misconceptions on the definition and measurement of ductility of nanostructured metals, which have led to the publications of problematic claims and data.

The biggest confusion is on the difference between ductility and plasticity. Plasticity is an important property for metallic materials, which could significantly affect their processing, shaping, and forming ability. Unfortunately, in the academic literature, these two terminologies are often mixed up and interchanged, which has raised serious issues and sometimes led to wrong and/or misleading scientific claims and statements. What is more problematic is that such publications often mislead the research community, especially junior researchers and students, as well as the public. To make things worse, plasticity and ductility are often not well defined in textbooks, e.g. Deformation and Fracture Mechanics of Engineering Materials [8]. These problems become more serious in recent years with the study of nanostructured metals, in which very small, non-standard samples are often used to characterize mechanical properties.

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In this article, we will first discuss the differences between ductility and plasticity, clarify some common misconceptions and confusions, and then briefly discuss recent progresses in improving the ductility of nanostructured metals.

## 2. Ductility

In the Wikipedia [https://en.wikipedia.org/wiki/Ductility], ductility is defined as 'a solid materials' ability to deform under *tensile stress*.' Quantitatively, ductility is usually measured as the elongation to failure, i.e. the total engineering strain at failure, from the tensile testing of standard large samples. Fig. 1 schematically shows a typical tensile specimen before and during strain localization (necking) during a tensile test, and Fig. 2 shows the corresponding engineering stress–strain curve. The total engineering strain at failure is defined as

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{\Delta l_u}{l_0} + \frac{\Delta l_n}{l_0} = \varepsilon_u + \varepsilon_n \tag{1}$$

where $l_0$ is the initial gage length, $\Delta l$ is the total gage length change after the tensile test, $\Delta l_u$ is the uniform gage length change during the tensile test, $\Delta l_n$ is the local length change in the necking segment, $\varepsilon_u$ is the uniform elongation, and $\varepsilon_n$ is the necking strain.

As shown in Fig. 2, the uniform elongation is determined by the maximum stress in the engineering stress–strain curve. In the true stress–strain curve obtained under a constant strain rate, it is often determined by the Considère criterion [4]:

$$\frac{d\sigma_t}{d\varepsilon_t} \geq \sigma_t \tag{2}$$

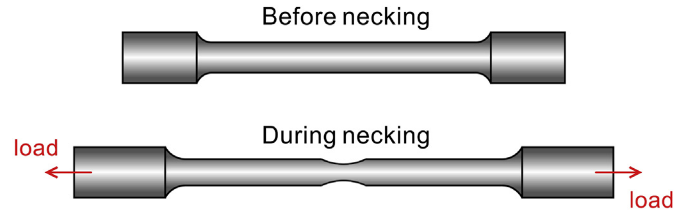

**Fig. 1.** Schematic illustration of sample geometry change before and during necking during a tensile test.

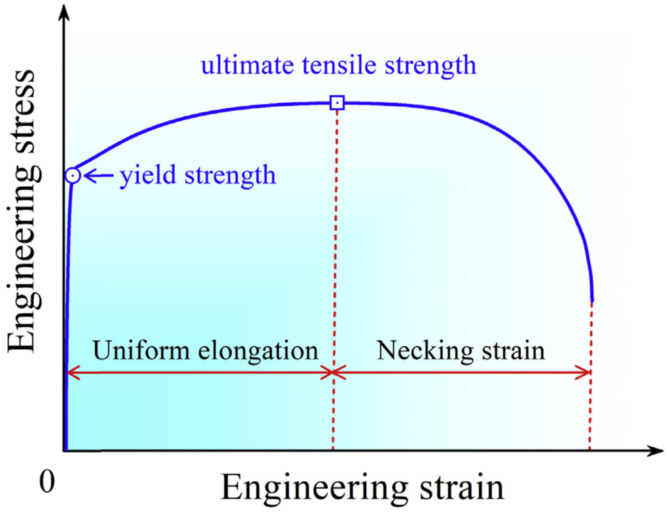

**Fig. 2.** Typical tensile engineering stress–strain curve.

where $\sigma_t$ is the true stress and $\varepsilon_t$ is the true strain. Note that the Considère criterion can be derived to agree with maximum stress criterion for the engineering stress–strain curve, i.e.

$$\frac{d\sigma_e}{d\varepsilon_e} \geq 0 \tag{3}$$

where $\sigma_e$ is the engineering stress and $\varepsilon_e$ is the engineering strain. In other words, the strain hardening rate largely determines the uniform deformation, which can be measured as the engineering strain at maximum engineering stress.

It should be noted that the Considère criterion does not consider the influence of strain rate sensitivity, which could also affect the ductility, especially at relatively high homologous temperatures and/or very small grain sizes in which the strain rate sensitivity is relatively high [5]. Hart's criterion [9] can take into account both the strain hardening and strain rate sensitivity:

$$\left(\frac{d\sigma_t}{d\varepsilon_t}\right)\frac{1}{\sigma_t} + m \geq 1 \tag{4}$$

where $m$ is the strain rate sensitivity.

For most nanostructured metals and alloys, the strain rate sensitivity $m$ is very small ($\ll$0.1), and therefore can be ignored, in which case the Considère criterion is applicable. There are also cases in which $m$ is relatively large at room temperature for nanostructured metals with low melting temperatures [5,10,11].

Application of the Hart's criterion is not easy because the strain rate sensitivity is usually not readily available. It is clear that the uniform deformation determined by the Hart's criterion (Eq. (4)) will be higher than what is determined by the Considère criterion (Eq. (2)) if the strain rate sensitivity is not negligible. In other words, the strain hardening required to maintain uniform elongation is smaller in the Hart's criterion than in the Considère criterion.

To increase the ductility of a metal, one should try to postpone unstable necking by increasing the uniform elongation. The Considère criterion tells us that we need to increase the strain hardening rate to delay localized deformation (necking). Hart's criterion implies that although increasing strain hardening is the primary way to increase ductility, enhancing the strain rate sensitivity also helps by some limited extents for most nanostructured metals.

Ductility is an important property for a metal to undergo tensile forming such as wire drawing or to serve under tensile load, such as rebars in a bridge beam. Without sufficient ductility, a structure or machine part serving under tensile load may fail catastrophically.

## 3. Plasticity

Plasticity is the ability of a solid material to undergo plastic deformation without fracture. The plasticity of a metal is mostly determined by its intrinsic crystal structure and available slip systems. According to von Mises's rule [12], five independent slip systems are required to plastically deform a metal without forming discontinuity (crack). Face-centered cubic (fcc) metals have 12 independent slip systems, whereas body-centered cubic (bcc) metals have 48 independent slip systems. Therefore, fcc and bcc metals usually have high plasticity and can be easily shaped and formed by rolling, forging, extrusion, etc. In comparison, hexagonal close packed (hcp) metals have less than five slip system and usually need deformation twinning to meet the von Mises's requirement, which is why deformation twinning is always activated during their deformation beyond a certain plastic strain. As a result, hcp metals have much lower plasticity than fcc and bcc metals. For example, hcp Ti cannot be deformed by equal channel angular pressing using