



Using the Hollomon Model to Predict Strain-Hardening in Metals

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Abstract: Stress – strain values obtained from tensile tests of aluminium and steel is used to evaluate the true stress – true strain values. The Hollomon's model is then used to predict the strain-hardening behavior in the two specimens. It is clearly seen that the strain-hardening behavior in metals can be described using the Hollomon's model. However, we have assumed that the onset of strain-hardening is at the yield point up until the ultimate tensile strength. The correlation between the experimental true stress – true strain values of aluminium and the calculated values using the Hollomon equation is much better than that of steel.

Keywords: Strain-Hardening, Tensile Strength, Hollomon's Model

1. Introduction

The elastic modulus of a material is an indication of the atomic binding forces and therefore the elastic properties of a material under loading. When a metal is subjected to increasing applied loads below its yield point, the strains are initially often proportional to the stress, and the material returns to its original shape or dimensions when the load is removed, this is an elastic behavior of the metal [1]. As the load is increased, the loads that exceed the yield point cause disproportionality between the strains and the loads. Upon unloading, the strains are not recovered completely. This irreversible deformation characterizes plastic deformation and where the strain-hardening phenomena sets in [2]. Industrial metallic alloys are polycrystalline materials comprised of grains of different sizes, orientation and shape. These features are what make materials anisotropic or isotropic.

Deformation that occurs beyond the point of yield especially at low temperatures, takes place by shear, or slip of one crystal plane over the other. This action is the result of the movement of microscopic defects such as dislocation through the crystal, occurring by consecutive annihilation and creation of new bonds with other atoms across the slip

plane [2]. The strain-hardening phenomenon is explained on the basis of dislocation–dislocation strain field interactions. The dislocation density in a metal increases with deformation or cold work, due to dislocation multiplication or the formation of new dislocations. Consequently, the average distance of separation between dislocations decreases. The dislocations are positioned closer together. On the average, dislocation–dislocation strain interactions are repulsive. The net result is that the motion of a dislocation is hindered by the presence of other dislocations. As the dislocation density increases, this resistance to dislocation motion by other dislocations becomes more evident. Thus, the imposed stress necessary to deform a metal increases with increasing cold work [3]. This phenomena according to the Hall-Petch relation shows that the smaller the grain size, the larger the flow stress. Though a single phase polycrystalline might have the same crystallographic structure, the grains might have different mechanical properties depending on the phase volume fractions, initial dislocation density or inclusions. For bulk materials, surface grains might have different microscopic behavior compared to the grains in the bulk material [17]. Metal forming processes such as forging, rolling and extrusion are based on the principles of strain hardening which uses strain accumulation and grain

refinement to obtain materials with an exceptional combination of high strength, stiffness and ductility. In view of this situation, engineers are engrossed on determining methods such as the finite element method (FEM) to acquire precise predictions about geometrical parts, post-forming characteristics and improving design processes. Bruschi *et al.* [13] studied the prediction of possible defects and failures on the basis of process parameters.

Over the years, several flow relationships have been proposed [5-11] to describe the tensile flow and strain-hardening behavior in metals. Constitutive models are explained at the microscopic level and the macroscopic level. The microscopic model shows a high level of accuracy in relation to the phase transformation and dislocation mechanics but are limited in their use, due to complex experimental procedures needed in obtaining information about material parameters [14, 15] while macroscopic models provide good compromise between model accuracy and simulation computational time and therefore are widely used [16]. Isotropic models, Kinematic models and a combination of both isotropic and kinematic models are three types of hardening models. The Isotropic hardening model is not a complex model so they are mostly used for industrial applications since they are able to predict the hardening behavior of a wide range of materials by expressing the proportional expansion of the initial yield surface [18]. The Kinematic hardening model on the other hand, although complex, has gained broad attention in recent years due to its ability to predict the Bauschinger effect [19, 20]. Therefore, a combination of the isotropic and kinematic models provide uniform expansion and translation in shape of the yield surface. The precision and complexity of models depend on the number of material parameters and history variables.

The Hollomon's equation which is a power law relating the true strain to the true stress is given by

$$\sigma_T = K \varepsilon_T^n \quad (1)$$

Where σ_T is the true stress, ε_T is the true strain, n is the strain-hardening exponent and K is the strength coefficient. In the Hollomon's expression, the strain-hardening exponent measures the ability of a metal to strain-harden, larger magnitudes indicate larger degrees of strain hardening. For most metals, the strain-hardening exponent falls between 0.10-0.50, however, perfectly elastic plastic-solids have a strain-hardening exponent of zero. The strain-hardening exponent and the strength coefficient are both determined from the logarithm of the true stress versus the logarithm of the true strain in the region of uniform elongation.

The Kocks-Mecking [11, 12] model assumes a constant strain rate for the evolution of dislocation structure with strain. The strain-hardening is controlled by packing and reordering of dislocations which are assumed to superimpose in an additive manner. The total elongations in a material during deformation has been known to originate from elastic and plastic contributions. Therefore, the plastic strain can be evaluated according to the expressions in equations 2-4.

$$\varepsilon_T = \varepsilon_p + \varepsilon_e \quad (2)$$

Where ε_T is the total strain in the metal, ε_p is the plastic strain and ε_e is the elastic strain.

However, the elastic strain is related to the elastic stress and elastic modulus according to Hooke's law given by:

$$\varepsilon_e = \frac{\sigma}{E} \quad (3)$$

Therefore, the plastic strain is given as

$$\varepsilon_p = \varepsilon_T - \frac{\sigma}{E} \quad (4)$$

The strain-hardening rate (θ) is therefore given as;

$$\theta = \frac{d\sigma}{d\varepsilon_p} = \theta_o \left[1 - \frac{\sigma}{\sigma_s} \right] \quad (5)$$

where $\frac{d\sigma}{d\varepsilon_p}$ is the strain-hardening rate, θ_o is the strain hardening coefficient which corresponds to the initial strain-hardening rate at $\sigma=0$ and σ_s is the saturation stress at high strains corresponding to conditions when the strain-hardening rate is zero. The deformation behavior at the grain scale of polycrystalline aluminium in uniaxial tension was found to be non-uniform at the early stage of plastic straining and the plastic deformation within the grains was found to be inhomogeneous by Sachtleber *et al.* [23]. With increasing applied strain, the deformation inhomogeneity of each grain and sub-grain increases [17].

However, in this paper we use the Hollomon's model to predict the strain-hardening behavior in aluminium and steel.

2. Results and Discussion

In predicting the strain-hardening behavior using the Hollomon model, we used stress-strain data obtained from tensile tests of steel and aluminium at room temperature. This is because, one of the most common mechanical stress-strain tests is performed in tension [21]. The stress-strain data are obtained directly during the course of the test and an inverse test is unnecessary, unlike in the bending test [22]. The tensile test can be used to ascertain several mechanical properties of materials that are important in design. The tensile test is popular since the properties obtained can be applied to design different components. The tensile test measures the resistance of a material to a static or slowly applied force. In performing the tensile tests, the initial diameters of the aluminium and mild steel samples were measured in order to be able to determine the engineering stress and an Avery testing machine was used for the tensile test with a strain rate of $5s^{-1}$. The samples were elongated till fracture.

We have assumed that strain-hardening primarily begins after the yield point of the metal and ends before ductile fracture. Therefore, we considered stress-strain values from the yield point up to the ultimate tensile stress. It is worth mentioning that since the power law is expressed in terms of true stress and true strain we calculated the true stress and true strain before plotting the values.

Results from the tensile tests showed that the force required to put the steel sample in tension was larger than that for the aluminium sample. This is in agreement with literature, although we did not perform microstructural analysis we know most steel types possess superior mechanical properties compared to the aluminium types. The steel sample possessed a lower yield point of 1.65GPa and an upper yield point of 1.67GPa which verifies the typical stress-strain behavior of carbon steel. An ultimate tensile strength value of 1.91GPa was also obtained for the steel sample. It was seen that for the steel sample, the ultimate tensile stress repeated three times but corresponded to different strains and this could be a result of inhomogeneity of plastic deformation within the grains which is caused by dislocation pile-ups or entanglements. On the other hand, the yield strength and ultimate tensile strength values of the aluminium sample were 240.958MPa and 275.384MPa respectively. The fracture strength of the aluminium and steel samples were 261.615MPa and 1.17GPa correspondingly. It is known that with increasing flow stress, the strain can be evenly distributed during deformation which leads to improved formability, so we can see that the mild steel would possess better forming abilities compared to the aluminium alloy. However, even though it is generally recognized that the formability increases with strain-hardening exponent, some materials have exhibited a different behavior. Copper has a lower formability than steel although it has a higher strain-hardening exponent [24, 25]. We have shown the True-Stress versus True-Strain curves for the aluminium sample in Figure 1. and for the steel sample in Figure 2.

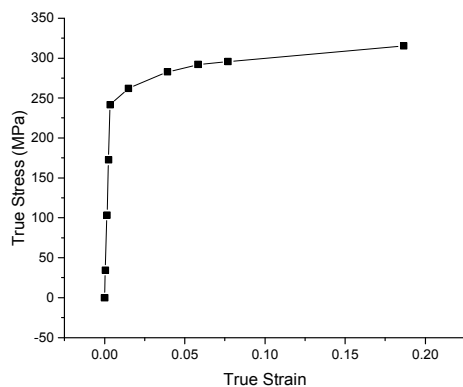


Fig. 1. True Stress vs. True Strain Curve of Aluminium.

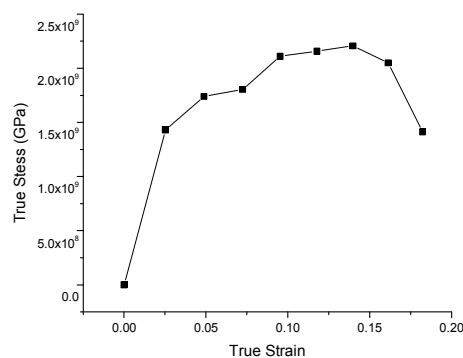


Fig. 2. True Stress vs. True Strain Curve of Steel.

In Figure 3. and Figure 4. we have shown a comparison of the experimental strain-hardening behavior and the calculated strain-hardening behavior for the aluminium and steel samples using the Hollomon's model. We based the experimental values used in the comparison on the assumption of work-hardening beginning at the onset of plastic deformation which is the deviation from the elastic linear behavior to the ultimate tensile strength. It was seen that the correlation between the experimental and calculated values was better for aluminium as compared to steel. This can be attributed to the fact that, although steel is an alloy, the presence of carbon makes the likelihood of the formation of an intermetallic compound between the parent element iron and carbon possible. Therefore, there could be an interstitial pinning of dislocations which causes the yield point values to somewhat fluctuate. This phenomenon is known as the yield point phenomenon and is very common in mild steel. We have also assumed that although the correlation is somehow close, the aluminium and steel specimen used for the tensile test might have been subjected to prior deformation. Although, it can be seen that the flow stress or the work-hardening behavior of metals can be predicted using mathematical models, especially the Hollomon's equation, obtaining detailed information about grain interaction during deformation using these models seem far-fetched. Therefore, we suggest that faster and detailed modelling techniques which takes into consideration all the inhomogeneities on the microstructural level to be able to investigate their effects on the macroscopic deformation behavior in metals.

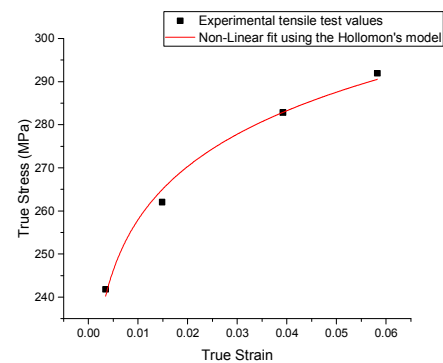


Fig. 3. Strain-hardening behavior of Aluminium.

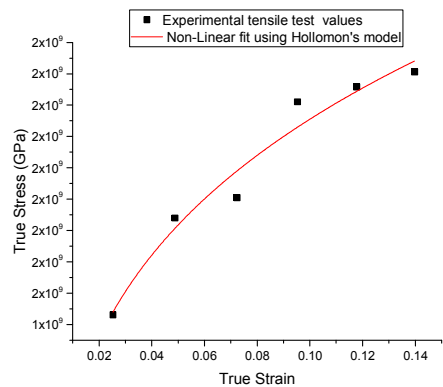


Fig. 4. Strain-hardening behavior of Steel.

3. Conclusions

The results indicate that the room temperature strain-hardening behavior in aluminium and steel can be described using the Hollomon model. However, the percentage of error in predicting the strain-hardening behavior in steel using the Hollomon's model might be greater than that of aluminium, since the fit between the experimental and calculated values of aluminum was better compared to steel. Therefore, further study is required to understand the mechanisms and underlying principles related to strain-hardening and the Hollomon equation.

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