**Effect of grain size on strength and strain rate sensitivity in metals**

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*Abstract*

*The effect of the grain size on the mechanical properties of metallic materials has been a topic of significant interest for researchers and industry. For many decades a relationship defining the mechanical strength proportional to the inverse of the square root of the grain size has been widely accepted despite some reports of deviations from this behavior. Nevertheless, the initial explanations for this relationship, based mainly on the activation of slip systems by dislocation pile-ups at grain boundaries, have provided essentially no predictive capability. Here we show that a physically-based model for grain boundary sliding predicts, in excellent agreement with experimental data, the flow stress for plastic deformation for a broad range of materials using the fundamental properties of each material over a wide range of grain sizes and testing conditions. This mechanism also successfully predicts the reported enhanced strain rate sensitivity in ultrafine and nanocrystalline materials at different temperatures.*

Keywords: deformation mechanisms; mechanical properties; nanocrystalline materials; strain rate sensitivity; ultrafine-grained materials

1. **Introduction**

One of the main goals of materials science is to advance the understanding of the relationship between structure and properties. In line with this goal, a significant effort has been dedicated to determining the effect of grain size on mechanical properties of metallic materials. The early papers by Hall [[1](#_ENREF_1)] and Petch [[2](#_ENREF_2)] have been considered a major step forward in this area and a relationship in which the mechanical strength is considered proportional to the inverse of the square root of the grain size has become widely accepted. The initial explanation for such relationship was based on the assumption that dislocation pile-ups at grain boundaries increased the local stress and thereby activated slip systems in the neighboring grain.

Early studies on the effect of grain size on the flow stress of polycrystalline metals were usually limited to grain sizes larger than ~10 μm which were produced by thermo-mechanical processing followed by annealing. The recent development of techniques capable of refining the grain sizes of metals to the sub-micrometer range provides, for the first time, a clearer representation of the effect of grain size on flow stress and also on the overall deformation behavior. A recent report summarized data from the literature for many different metals and showed that the models currently available only predict the observed trends by incorporating multiple adjustable parameters [[3](#_ENREF_3)].

Research on the mechanical behavior of ultrafine-grained metals (grain size *d* < 1 μm) revealed several interesting features such as different trends in the relationships between mechanical strength and grain size including grain refinement softening in some examples, an absence of strain hardening in most ultrafine-grained materials and enhanced contributions from grain boundary sliding to the overall deformation. The lack of a strain hardening capability in ultrafine-grained metals is considered the fundamental parameter governing the so-called paradox of strength and ductility since it plays a major role in the ability of a material to pull out in tension by a sufficient elongation. Thus, the strengthening effect obtained by grain refinement is accompanied by a concomitant decrease in ductility.

The enhanced contribution of grain boundary sliding to the deformation of ultrafine-grained materials is associated with an enhanced strain rate sensitivity which is also an important parameter in determining the ability to stretch in tension. In fact, the occurrence of superplastic flow, a phenomenon usually observed at high temperatures in which the material stretches over 400% in tension before failure [[4](#_ENREF_4)], is attributed to relatively high values of the strain rate sensitivity of >0.4. This parameter is generally not considered in evaluating the behavior of coarse-grained metals at room temperature because its value is negligible in these conditions. However, several reports demonstrate that some ultrafine-grained metals may exhibit high strength and good ductility due to an enhanced strain rate sensitivity thereby apparently overcoming the paradox of strength and ductility [[5-7](#_ENREF_5)].

It was demonstrated recently that an adjustment to the mechanism of high temperature grain boundary sliding [[8](#_ENREF_8)] can effectively predict the behavior of ultrafine-grained materials at low temperatures [[9](#_ENREF_9)] and initial observations suggest that this mechanism may also explain the relationship between the initial flow stress for plastic deformation of coarse-grained metals. The only difference between coarse-grained and ultrafine-grained metallic behavior is observed after the onset of plastic deformation as the former displays strain hardening, thereby increasing the flow stress during deformation, and the latter deforms under conditions of a near steady-state flow stress due to the lack of strain hardening.

The model is based on the fundamental assumption that grain boundary sliding is the rate-controlling flow mechanism in the absence of the formation of any major dislocation substructures such as dislocation cells and subgrain boundaries within the interiors of the grains. Thus, extrinsic dislocations at the grain boundaries glide under the action of external shear stresses causing grain boundary sliding and activating dislocation sources in neighboring grains at the triple junctions. The dislocations in the next grains slip and pile up at the opposite grain boundaries building up stresses and activating dislocation climb. Multiple experimental examples are available supporting this model and comprehensive details are given elsewhere [[9](#_ENREF_9)]. It is important to note also that dislocation emission from grain boundaries and dislocation absorption in grain boundaries was observed by transmission electron microscopy during *in situ* compression straining of an ultrafine-grained steel [[10](#_ENREF_10)]. The present work aims to evaluate the predictive capability of the model, covering both the relationship between flow stress and grain size and the relationship between strain rate sensitivity and grain size, for a very broad range of metals.

1. **Model and validation procedure**

A detailed description of the deformation mechanism for high temperature grain boundary sliding is available elsewhere [[8](#_ENREF_8)] and the adjustment and validation for low temperature deformation is discussed in a recent report [[9](#_ENREF_9)]. It is important to note that the grain size plays a major role in this mechanism since it affects the rate of sliding, the pile-up length and the climb distance [[8](#_ENREF_8)]. Thus, it is possible to reach the relationship between flow stress (σ), strain rate () and grain size (*d*) as follows [[9](#_ENREF_9)]:

(1)

where σ0 is a threshold stress, *G* is the shear modulus, *k* is Boltzmann’s constant, *T* is the absolute temperature, *b* is the Burgers vector modulus, δ is the grain boundary width (which is usually considered as 2×*b*) and *Dgb* is the coefficient for grain boundary diffusion. It follows that *G*, *b* and *Dgb* are the fundamental properties of metals and their values for different metals are given in Table 1 [[11](#_ENREF_11), [12](#_ENREF_12)]. The values for the threshold stress were estimated from best fits with the experimental data. It is important to note that a complete description of the deformation behavior of metals should incorporate an analysis of the contribution of different parameters such as lattice friction and solid solution strengthening to the threshold stress. This is beyond the scope of the present work which focuses instead on the effect of grain size. Therefore, the threshold stress is considered as a constant in the present analysis.

It is important to note that the present model predicts a relationship in which the flow stress is inversely proportional to the square root of the grain size, in agreement with most of the experimental observations, for conditions in which the value within the *ln* function in eq. (1) is very large. This situation can be predicted for coarse-grained materials having low coefficients of grain boundary diffusion and tested at high strain rates. Alternatively, deviations from this relationship are expected at very fine grain sizes, at low strain rates and in situations where the coefficient of grain boundary diffusion is significant, such as at high temperatures and in materials with low melting temperatures.

The predictions of the model for different metals were compared to data in the literature to provide a firm validation of this approach. A large fraction of the data was extracted from a recent review [[3](#_ENREF_3)]. However, a small number of the results was not included in the present analysis due to uncertainties associated with some experimental procedures. Thus, most results from nano-indentation tests were excluded from the present analysis because this test can overestimate the strength of the material. Also, grain size measurements based solely on X-ray diffraction measurements were not included in the analysis because this technique can underestimate the grain size. Additional data were incorporated to provide a direct and comprehensive comparison with more than ~180 separate reports.

As the present model defines the grain size as the three-dimensional grain size, it is expected that a large fraction of the data available in the literature will provide underestimated values. However, the reported grain size was considered in the plots except for reports which explicitly used the “mean linear intercept” length. In these cases the reported values were multiplied by a factor of 1.74 which serves to correlate the mean linear intercept length to the three-dimensional grain size [[13](#_ENREF_13)].

Most of the data considered in the present analysis were obtained from pure metals. However, some results were also included for materials containing alloying elements or second phase particles. The results for f.c.c. iron were based on data from 304, 316 and 321 austenitic stainless steel.

The strain rate sensitivity parameter, *m*, is defined as . Therefore, the relationship for *m* may be expressed in terms of the same fundamental properties of the metals including the threshold stress, the deformation temperature, the strain rate and the grain size, so that

(2)

where

(3)

and

(4)

It is important to note that the threshold stress is a thermally-activated parameter and is expected that it will be a function of temperature and strain rate. The derivative of the strain rate sensitivity in eq. 2 is an approximation since it considered the threshold stress as a constant. Therefore, it is reasonable to assume that eq. 2 provides a lower bound prediction for strain rate sensitivity. It is expected that the predictions from eq. 2 will be more accurate for materials in which there is a reduced contribution from the threshold stress.

Although the present model predicts the flow stress for a broad range of grain sizes, it is anticipated that coarse-grained materials will develop dislocation substructures during deformation and this will change the deformation mechanism and cause strain hardening. Therefore, the present mechanism is expected to be rate-controlling only in situations where the grain size is smaller than the stable subgrain size so that dislocation substructures are unable to develop. It is known that the average subgrain size, λ, depends primarily on the stress level and the following relationship is valid for metals [[14](#_ENREF_14)], ceramics [[15](#_ENREF_15)] and geological materials [[16](#_ENREF_16), [17](#_ENREF_17)]:

(5)

where ζ is a constant having a value equal to ~20. Thus, it is possible to determine the transition grain size where *d* = λ for each metal for all deformation conditions.

Figure 1 shows an example of plots of the flow stress predicted by the present model, considering room temperature and a strain rate of 10-4 s-1, as a function of the grain size and the subgrain size for α-Fe. The curves intercept at *d* ≈ 0.3 μm. Therefore, the present model predicts the strain rate sensitivity for b.c.c. iron for *d* < 0.3 μm.

1. **Flow stress as a function of the grain size**

Figure 2 shows the data for flow stress plotted as a function of grain size for b.c.c. metals including experimental data for Cr [[18-21](#_ENREF_18)], α-Fe [[22-39](#_ENREF_22)], Mo [[40-46](#_ENREF_40)] , Nb [[47-58](#_ENREF_47)], V [[46](#_ENREF_46), [59-65](#_ENREF_59)] and W [[66](#_ENREF_66), [67](#_ENREF_67)]. Figure 3 shows the flow stress plotted as a function of grain size for f.c.c. metals including experimental data for Ag [[21](#_ENREF_21), [68-73](#_ENREF_68)], Al [[74-91](#_ENREF_74)], Cu [[92-110](#_ENREF_92)], Ni [[111-122](#_ENREF_111)] and γ-Fe [[24](#_ENREF_24), [123-130](#_ENREF_123)]. Finally, Fig. 4 shows the flow stress plotted as a function of grain size for h.c.p. metals including experimental data for Cd [[131](#_ENREF_131), [132](#_ENREF_132)], Mg [[133-142](#_ENREF_133)], Ti [[143-155](#_ENREF_143)], Zn [[156-162](#_ENREF_156)] and Zr [[163-168](#_ENREF_163)]. A strain rate of 10-4 s-1 was taken as appropriate for quasi-static testing and each combination of symbols and color refers to different sets of data. The prediction from the model, considering a threshold stress estimated from a best fit procedure for each metal, is also plotted as a continuous line in each graph. Thus, inspection shows that an excellent agreement is achieved between prediction and experimental data for all materials without incorporating any adjustable parameters.

The extent of the experimental data for some metals such as W and Cd is limited and this reduces the accuracy in estimating the threshold stress. A significant scatter in the experimental data is observed, especially in the range of coarser grain sizes, in some metals such as aluminum, copper and titanium. In practice, a degree of scatter is expected in experimental data due to multiple sources which include variations in composition of the material, uncertainties regarding the level of stress considered for the onset of plastic deformation and determinations of the values of grain sizes. Although the model agrees well with the experimental data for Al and Cu, there appears to be two trends in Ti which affect mostly the threshold stress but without compromising the prediction from the model.

The data for magnesium is limited to a maximum grain size of 10 μm because this material displays twinning-controlled deformation at coarser grain sizes and therefore the present model is not applicable under these conditions. An earlier analysis [[9](#_ENREF_9)] showed the present model agrees with experimental data for Mg under conditions where the deformation is slip-controlled such as fine grain sizes and higher temperatures.

It is important to note that the model predicts a change in slope in the σ vs *d* plots at very fine grain sizes in Ag and Al which agrees with the experimental trends in this range. Also, the model predicts a decrease in flow stress with decreasing grain size in materials with higher grain boundary diffusion coefficients at room temperature, such as Mg and Zn, and this also agrees with experimental data for these materials although the precise grain size for the onset of this phenomenon may vary.

Molecular dynamics simulations have been used to evaluate the flow stress of copper with grain sizes in the range between 5 to 50 nm at a strain rate of ~5 × 108 s-1 [[110](#_ENREF_110)]. The prediction from the model, considering this strain rate, is plotted as a gray dashed line and agrees with the data for *d* > ~10 nm. A change in deformation mechanism and grain refinement softening is predicted for *d* < ~10 nm in Cu [[98](#_ENREF_98), [110](#_ENREF_110)] suggesting that a grain size of ~10 nm is a limiting condition for validity of the present model in this material.

Grain refinement softening was reported recently in Ni and Ni-Mo alloys at *d* < ~10 nm and it was shown that this effect is associated with strain-induced grain boundary migration [[122](#_ENREF_122)]. It was further demonstrated that the grain boundaries may be stabilized by a thermal treatment preventing their migration and, as a consequence, grain refinement strengthening was observed even at *d* < 10 nm. It is interesting to note that the σ × *d* data from the stabilized Ni and Ni-Mo alloys (green squares in plot for Ni in Fig. 2) agree with the present model.

1. **Predictions for strain rate sensitivity**

Experiments on ultrafine and nanocrystalline materials have revealed some unpredicted results of high ductility at low temperatures. These results, which were attributed to enhanced strain rate sensitivity, include elongations over 10% at room temperature in materials with high strength [[5](#_ENREF_5), [6](#_ENREF_6)] and evidence of exceptional elongations over 100% under special conditions [[169-172](#_ENREF_169)].

Figure 5 shows the strain rate sensitivity, *m*, predicted for different materials at different testing conditions considering estimated values of the threshold stress. Experimental data from the literature for α-Fe [[23](#_ENREF_23), [173-175](#_ENREF_173)], Zn [[157](#_ENREF_157), [162](#_ENREF_162), [176-181](#_ENREF_176)], Cu [[182-189](#_ENREF_182)] and Al [[6](#_ENREF_6), [74](#_ENREF_74), [190-193](#_ENREF_190)] are also plotted for comparison. The strain rate sensitivity data for ultrafine-grained and nanocrystalline materials have been reviewed [[194](#_ENREF_194)] and a trend of increasing *m* with decreasing grain size was observed in f.c.c. and h.c.p. metals. This agrees with the predictions from the present model which are shown as continuous lines for Cu, Al and Zn in Fig. 5. This trend is more pronounced in Zn due to the larger grain boundary diffusion coefficient. However, it was reported that b.c.c. metals display the opposite trend in which *m* decreases with decreasing grain size [[194](#_ENREF_194)]. It is expected that the threshold stress will play a major role in the value of *m* for coarse-grained metals and this effect is more pronounced in b.c.c. metals which usually display higher threshold stresses than f.c.c. metals. Such an analysis is out of the scope of the present paper. Nevertheless, a very careful review of the data for Fe shows a minor increase in *m* with decreasing grain size for *d* < 300 nm which is the range where the present mechanism becomes rate-controlling as shown in Fig. 1.

The present model predicts an increase in *m* with decreasing testing strain rate and with increasing testing temperature. These effects are shown in Fig. 5 for Cu and Al, respectively, and the prediction also agrees with experimental data. Thus, it is possible to plot the predicted values of *m,* for a fixed grain size, as a function of both strain rate and temperature and an example is shown in Fig. 6 for Mg for temperatures lower than ~0.5 of the absolute melting temperature and considering a grain size of 0.5 μm. In order to estimate the threshold stress, the predictions for stress at 300, 373, 423 and 473 K were compared to data in the literature. Thus, values of σ0 of 80, 50, 20 and 2 MPa were considered as the threshold stresses for these four temperatures, respectively. The predictions of m for these temperatures, in the strain rate range between 10-­5 - 10-1 s-1, were then interpolated to generate the map.

It is interesting to note that the model predicts a broad range of combinations of temperature and strain rate in which *m* > 0.1 which suggests that it should be feasible to observe large elongations in tension in ultrafine-grained magnesium even within this low temperature range. This is in agreement with multiple reports of exceptional and even superplastic elongations in Mg and its alloys at low temperatures up to 423 K [[169](#_ENREF_169), [195](#_ENREF_195), [196](#_ENREF_196)]. It is noted also that *m* increases and the optimum value moves to faster strain rates with increasing temperature and this agrees with an experimental observation of a record elongation of >3000% at 473 K [[197](#_ENREF_197)] and the development of high strain rate superplasticity at 493 K [[198](#_ENREF_198)] in an ultrafine Mg alloy.

The ability to predict high values of strain rate sensitivity in ultrafine-grained metallic materials is of great interest, especially at temperatures lower than ~0.5 of the melting temperature where this parameter is usually negligible for coarse-grained materials. By contrast, there are multiple reports of exceptional ductilities at low temperatures in ultrafine-grained metals [[5](#_ENREF_5), [169](#_ENREF_169), [170](#_ENREF_170), [199](#_ENREF_199)]. Figure 7 shows examples of the elongations (Δ*L*/*L*0) reported at low temperatures in Al [[6](#_ENREF_6), [192](#_ENREF_192), [193](#_ENREF_193), [200](#_ENREF_200)], Cu [[201](#_ENREF_201), [202](#_ENREF_202)], Fe [[203](#_ENREF_203)], Mg [[169](#_ENREF_169), [195-197](#_ENREF_195), [204](#_ENREF_204), [205](#_ENREF_205)], Ni [[170](#_ENREF_170), [206](#_ENREF_206)] and Zn-based alloys [[181](#_ENREF_181)] plotted as a function of *m* as predicted by the model. As expected, there is a general trend of increasing elongation with increasing *m*. Despite the scatter in the data, it is clear that elongations of ~100% and larger can be obtained under conditions in which the present model predicts *m* > ~0.1.

1. **Discussion**

The present results show a very good agreement between the predictions from the model and experimental data for the relationship between flow stress and grain size (*σ* vs *d*) for a broad range of grain sizes in different materials. Such agreement is attained without the need for incorporating any adjustable parameters other than the threshold stress. Other mechanisms have been suggested to explain the relationship between flow stress and grain size and a recent review [[3](#_ENREF_3)] showed that these mechanisms fail to provide a good agreement with general trends from different sets of experimental data. It is important to note that the deformation mechanism developed and utilized in the present analysis exhibits a major difference to most of the mechanisms available in the literature since the present mechanism predicts that the relationship between flow stress and grain size is thermally-dependent. By comparison, the temperature dependence of this relationship is usually limited to the effect of temperature on the material shear modulus in other mechanisms.

The present mechanism predicts that the temperature and the grain boundary diffusion coefficient (which depends on the temperature) play a significant role in the *σ* vs *d* relationship. This explains the capability of the present model to predict grain refinement softening in materials with significant grain boundary diffusion coefficients at room temperature such as Mg and Zn which is in agreement with experimental observations. Although the available experimental reports for the *σ* vs *d* relationship at different temperatures are limited, they usually confirm that it is affected by the temperature. For example, a slight decrease in the *σ* vs *d* slope was observed experimentally in Ti even after normalizing the data by the thermal variation of the shear modulus [[151](#_ENREF_151)]. Also, the slope of the *σ* vs *d* relationship for a Mg alloy, in slip-dominated flow, was found to vary significantly with temperature and was related to the Zener-Hollomon parameter [[207](#_ENREF_207)]. Finally, an earlier analysis showed there was excellent agreement between the predictions from the present model and data for different metals at high temperatures [[9](#_ENREF_9)].

The present model also predicts that the strain rate can play a significant role in the *σ* vs *d* relationship. The contribution of the strain rate will depend on other parameters and basically its role increases with decreasing grain size and increasing grain boundary diffusion coefficient. Thus, it is expected that experiments at room temperature in coarse-grained materials with high melting points will display almost an insignificant dependence on strain rate. However, the strain rate may affect materials that exhibit a significant grain boundary diffusion coefficient at room temperature. This agrees with experimental observations of the occurrence of different *σ* vs *d* relationships when testing Mg at different strain rates [[142](#_ENREF_142)].

The present results also show very good agreement between the predictions of strain rate sensitivity and values determined experimentally in ultrafine-grained materials. This includes predictions of enhanced strain rate sensitivities in materials and testing conditions which have been associated with experimental observations of extraordinary elongations in ultrafine and nanocrystalline materials.

It is interesting to note that, in a study of a Zn-0.4% Al alloy about 50 years ago [[160](#_ENREF_160)], it was explicitly written that “*This work suggests that, for given conditions of temperature and strain-rate, there is a critical grain size, above which dislocation interaction with workhardening will occur, and below which dislocation climb and annihilation (dynamic recovery) will take place and in this latter case superplasticity will be observed.*” This observation is remarkably consistent with the present model. Thus, it is possible to re-write this sentence, with minor adjustments, to state that there is a critical grain size above which a dislocation interaction with workhardening and subgrain development will occur, and below which dislocation climb and annihilation (dynamic recovery) will take place, and in this latter condition grain boundary sliding will be the rate-controlling mechanism. The occurrence of true superplasticity, which is also controlled by a grain boundary sliding mechanism and is associated with elongations larger than ~400%, is limited to conditions where the model predicts a strain rate sensitivity larger than ~0.4. These conditions will include low values of threshold stress and will depend on relevant combinations of grain sizes, strain rates and temperatures. For example, the model predicts, in agreement with experimental observations, high values of strain rate sensitivities at low temperatures in ultrafine-grained materials tested at low strain rates, at high strain rates in ultrafine-grained materials tested at moderate temperatures and in fine-grained materials tested at high temperatures and moderate strain rates.

1. **Summary and conclusions**
2. This report demonstrates that a deformation mechanism based on the assumption that grain boundary sliding activates dislocation sources, generating pile up and activating dislocation climb, provides the best prediction for the relationship between grain size and flow stress for a broad range of metals. The model predicts the flow stress as a function of temperature and strain rate for a very broad range of grain sizes. The model also predicts the strain rate sensitivity for metals with grain sizes smaller than the stable sub-grain size.
3. It is shown that the predictions from the model display remarkably good agreement with experimental data from ~180 reports in the literature based only on the fundamental properties of each metal and the threshold stress.
4. The model predicts that the flow stress is proportional to the inverse of the square root of the grain size for coarse-grained materials tested at low temperatures and moderate strain rates. Deviations from this behavior, including grain refinement softening, are predicted for ultrafine-grained metals with low melting points in agreement with experimental data.
5. The model also predicts, in agreement with experiments, the enhanced strain rate sensitivity observed in ultrafine-grained and nanocrystalline metals. The model provides, therefore, the capability of tailoring grain size and deformation conditions in selected materials in order to attain high strain rate sensitivity and high ductility.

**Acknowledgements:**

R.B.F. acknowledges financial support from CNPq (grant #302445/2018-8) and FAPEMIG (grant TEC-PPM-00324-17). T.G.L. was supported by the European Research Council under ERC Grant Agreement No. 267464-SPDMETALS.

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Table 1 – Fundamental properties of different metals [8,9] and the value of threshold stress estimated from the best fit to experimental data.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Material | *b* (nm) | *G* (MPa) \* | Grain boundary diffusion | | σ0 (MPa) (at 300 K) |
| *δD*0 (m3/s) | *Q*gb (kJ/mol) |  |
| Al | 0.286 | 29500 – 13.6 × *T* | 5 × 10-14 | 84 | 2 |
| Ag | 0.286 | 29900 – 11.6 × *T* | 4.5 × 10-15 | 90 | 10 |
| Cd | 0.293 | 36100 – 27.6 × *T* | 5 × 10-14 | 54.4 | 10 |
| Cr | 0.250 | 135000 – 29.5 × *T* | 5 × 10-15 | 192 | 200 |
| Cu | 0.256 | 47100 – 16.7 × *T* | 5 × 10-15 | 104 | 10 |
| Fe (b.c.c.) | 0.248 | 72600 – 28.7 × *T* | 1.1 × 10-12 | 174 | 70 |
| Fe (f.c.c.) | 0.258 | 93200 – 40.7 × *T* | 7.5 × 10-14 | 159 | 150 |
| Mg | 0.320 | 19200 – 8.8 × *T* | 5 × 10-12 | 92 | 80 |
| Mo | 0.273 | 140000 – 19.7 × *T* | 5.5 × 10-14 | 263 | 150 |
| Nb | 0.286 | 44300 | 5 × 10-14 | 263 | 100 |
| Ni | 0.249 | 87700 – 29.3 × *T* | 3.5 × 10-15 | 115 | 10 |
| Ti (h.c.p.) | 0.295 | 51700 – 27.0 × *T* | 3.6 × 10-16 | 97 | 250 |
| V | 0.263 | 52700 – 8.7 × *T* | 5 × 10-14 | 209 | 150 |
| W | 0.274 | 165000 – 16.6 × *T* | 3.1 × 10-13 | 385 | 500 |
| Zn | 0.267 | 60000 – 35.6 × *T* | 1.3 × 10-14 | 60.5 | 20 |
| Zr | 0.323 | 40000 – 21.2 × T | 8.2 × 10-14 | 124 | 300 |

\*adapted into a fundamental relationship incorporating the temperature dependence

Figures



Figure 1 – Prediction of the minimum grain size that will not develop a subgrain structure during plastic deformation in α-Fe.



Figure 2 - Flow stress plotted as a function of grain size for b.c.c. metals including experimental data for Cr [[18-21](#_ENREF_18)], α-Fe [[22-39](#_ENREF_22)], Mo [[40-46](#_ENREF_40)] , Nb [[47-58](#_ENREF_47)] , V [[46](#_ENREF_46), [59-65](#_ENREF_59)] and W [[66](#_ENREF_66), [67](#_ENREF_67)].



Figure 3 – Flow stress plotted as a function of grain size for f.c.c. metals including experimental data for Ag [[21](#_ENREF_21), [68-73](#_ENREF_68)], Al [[74-91](#_ENREF_74)], Cu [[92-110](#_ENREF_92)], Ni [[111-122](#_ENREF_111)] and γ-Fe [[24](#_ENREF_24), [123-130](#_ENREF_123)].



Figure 4 – Flow stress plotted as a function of grain size for h.c.p. metals including experimental data for Cd [[131](#_ENREF_131), [132](#_ENREF_132)], Mg [[133-142](#_ENREF_133)], Ti [[143-155](#_ENREF_143)], Zn [[156-162](#_ENREF_156)] and Zr [[163-168](#_ENREF_163)].



Figure 5 – Strain rate sensitivity (*m*) predicted by the present model for different materials and different testing conditions combined with experimental data for α-Fe [[23](#_ENREF_23), [173-175](#_ENREF_173)] , Zn [[157](#_ENREF_157), [162](#_ENREF_162), [176-181](#_ENREF_176)] , Cu [[182-189](#_ENREF_182)] and Al [[6](#_ENREF_6), [74](#_ENREF_74), [190-193](#_ENREF_190)] from the literature for comparison



Figure 6 – Strain rate sensitivity map estimated for Mg.



Figure 7 – Elongation to failure observed in experiments in Al [[6](#_ENREF_6), [192](#_ENREF_192), [193](#_ENREF_193), [200](#_ENREF_200)], Cu [[201](#_ENREF_201), [202](#_ENREF_202)], Fe [[203](#_ENREF_203)], Mg [[169](#_ENREF_169), [195-197](#_ENREF_195), [204](#_ENREF_204), [205](#_ENREF_205)], Ni [[170](#_ENREF_170), [206](#_ENREF_206)] and Zn [[181](#_ENREF_181)] at temperatures <0.5 *T*m plotted as a function of the predicted value of *m*.