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Research Article

A Modified Eyring Equation for Modeling Yield and Flow Stresses of Metals at Strain Rates Ranging from 10^{-5} to $5 \times 10^{4}\,s^{-1}$

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In several industrial applications, metallic structures are facing impact loads. Therefore, there is an important need for developing constitutive equations which take into account the strain rate sensitivity of their mechanical properties. The Johnson-Cook equation was widely used to model the strain rate sensitivity of metals. However, it implies that the yield and flow stresses are linearly increasing in terms of the logarithm of strain rate. This is only true up to a threshold strain rate. In this work, a three-constant constitutive equation, assuming an apparent activation volume which decreases as the strain rate increases, is applied here for some metals. It is shown that this equation fits well the experimental yield and flow stresses for a very wide range of strain rates, including quasi-static, high, and very high strain rates (from 10^{-5} to $5 \times 10^{4}\,s^{-1}$). This is the first time that a constitutive equation is showed to be able to fit the yield stress over a so large strain rate range while using only three material constants.

1. Introduction

The steel and metallic materials are largely used in several industrial fields, for example, automobile, naval, aeronautical, and military industries. In these applications, transportation vehicles have to be designed against impact loads. Thus, developing constitutive equations that take into account the strain rate sensitivity of metals is of major importance.

The split Hopkinson bar was largely applied to evaluate the strain rate sensitivity of materials at high strain rates; that is, $\dot{\varepsilon} \sim< 5000\,s^{-1}$ [1–3]. At very high strain rates ($\dot{\varepsilon} >\sim 5000\,s^{-1}$), the direct-impact Hopkinson bar is now increasingly used [4, 5]. Based on the available experimental data, several constitutive equations were proposed in the open literature [6–9]. Johnson and Cook [10] have proposed a phenomenological equation that includes hardening, temperature, and strain rate effects. This equation has been widely used [11–13] and included in several commercial finite-element software types; this is mainly due to the reduced number of constants that it used and the separation of the hardening, temperature, and strain rate effects. It was then applied to model the strain rate sensitivity mainly for metallic alloys as for titanium [14, 15], copper [16], aluminum [17, 18], and steel [19–22] alloys.

The Johnson-Cook equation assumes that the yield and flow stresses are linearly increasing in terms of the logarithm of strain rate. Nevertheless, this assumption is mostly valid up to a threshold strain rate. The strain rate sensitivity highly increases at high strain rates [23, 24], indeed. Several modifications have then been proposed to extend the validity of the Johnson-Cook model up to the very high strain rate range [24–27].

The original Johnson-Cook model uses two constants to take into consideration the strain rate sensitivity. The modified Johnson-Cook equations involve at least four constants in order to catch the stress behavior at very high strain rate. Recently, El-Qoubaa and Othman [28] proposed a modified Eyring equation [29] to model the strain rate sensitivity of the polyetheretherketone's yield stress. Within the framework of the Eyring theory, yielding is a thermally activated process. Ree and Eyring [30] used relaxation processes. Fotheringham et al. [31, 32] introduced the idea of the cooperative motion of polymer chain segments. Richeton et al. [33] used the cooperative motion theory and introduced the Arrhenius law for the horizontal and vertical shifts. El-Qoubaa and Othman [28, 34] used an apparent activation volume which is decreasing for increasing strain rate. Their equation involves three material constants.

In this work, El-Qoubaa and Othman's equation is examined regarding the yield stress and the flow stress at a given plastic strain, of several metals. Besides, the methodology, to obtain a reasonable first guess of the materials constants, is detailed.

2. Constitutive Equation

Johnson and Cook [10] have proposed that the flow stress of metals is obtained in the following form:

$$\sigma = \left(A + B\varepsilon_p^n\right)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right), \quad (1)$$

where ε_p, $\dot{\varepsilon}$, $\dot{\varepsilon}_0$, T, T_r, and T_m are the plastic strain, strain rate, reference strain rate, temperature, room temperature, and melting temperature, respectively, and A, B, C, n, and m are four material constants. The yield stress, at room temperature, is obtained by considering $\varepsilon_p = 0$ and $T = T_r$. Thus,

$$\sigma_y^{JC} = A\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right). \quad (2)$$

With no loss of generality, the reference strain $\dot{\varepsilon}_0$ can be fixed to $1\,\mathrm{s}^{-1}$. Consequently, two materials constants, namely, A and C, are needed to predict the strain rate sensitivity of metals' yield stress. Similarly, two constants are needed to predict the strain rate sensitivity of the flow stress at a given plastic strain.

Even though the Johnson-Cook equation is a phenomenological model, it can find some foundation in the work of Eyring [29] who argued that yielding is a thermally activation process. In this framework, the following equation for the yield stress is established:

$$\frac{\sigma_y^E}{T} = A_\alpha\left(\frac{Q_\alpha}{RT} + \ln\left(2C_\alpha\dot{\varepsilon}\right)\right), \quad (3)$$

where R is the universal gas constant, A_α and C_α are two material constants, and Q_α is the activation energy of the α-transition. The Eyring equation can also be rewritten as

$$\sigma_y^E = \sigma_0 + \frac{kT}{V_0}\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right), \quad (4)$$

where k is the Boltzmann constant. Here also, two constants σ_0 and V_0 are needed to define the strain rate sensitivity of the yield stress. σ_0 is yield stress at a strain rate $\dot{\varepsilon} = \dot{\varepsilon}_0 = 1\,\mathrm{s}^{-1}$ and V_0 is the activation volume which is assumed to be constant.

El-Qoubaa and Othman [28] argued for the use of an apparent activation volume that is decreasing with increasing strain rate. More precisely, they suggested that the logarithm of the activation volume is linearly decreasing in terms of strain rate. The apparent activation volume is then written as

$$V^* = V_0\exp\left(-\sqrt{\frac{\dot{\varepsilon}}{\dot{\varepsilon}_c}}\right), \quad (5)$$

where $\dot{\varepsilon}_c$ is critical strain rate. Substituting the constant activation volume V_0 in (4) by the strain-rate-sensitive activation volume of (5) yields a new equation of the yield stress:

$$\sigma_y^{ME} = \sigma_0 + \frac{kT}{V_0}\exp\left(\sqrt{\frac{\dot{\varepsilon}}{\dot{\varepsilon}_c}}\right)\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right). \quad (6)$$

This modified Eyring equation needs now three constants, σ_0, V_0, and $\dot{\varepsilon}_c$, to predict the strain rate sensitivity of the yield stress. This equation can also be used to model the flow stress at a constant plastic strain.

Equation (6) has two main advantages. First, it uses a reduced number of materials constants, namely, 3 constants, whereas the modified Johnson-Cook equations use at least four constants. Second, the three material constants are easily interpretable. Hence, σ_0 is no more than the yield at a strain rate of 1/s. V_0 is the activation volume of the α-transition of the Eyring equation. Finally, $\dot{\varepsilon}_c$ separates the strain rate range in two parts. For lower strain rates ($\dot{\varepsilon} \ll \dot{\varepsilon}_c$), the yield stress increases linearly in terms of the logarithm of strain rate. At high strain rates, the strain rate sensitivity highly increases with increasing strain rate. These interpretations help in establishing a methodology to obtain a first guess of these constants.

The identification of the materials constants is then divided in two steps. Firstly, a first guess is determined knowing the above interpretations of these constants. Secondly, an optimization procedure is used to better fit the experimental data. More precisely, the first-guess values of σ_0 and V_0 will be determined from two points in the low strain rate range assuming a linear variation of yield stress in terms of the logarithm of strain rate.

Let $\widehat{\sigma}_1$ and $\widehat{\sigma}_2$ be the yield stress measured for two strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$, respectively, of the low strain rate range. The first guess of the constants σ_0 and V_0 is

$$\sigma_0^{\text{guess}} = \frac{\widehat{\sigma}_1\ln\left(\dot{\varepsilon}_2\right) - \widehat{\sigma}_2\ln\left(\dot{\varepsilon}_1\right)}{\ln\left(\dot{\varepsilon}_2/\dot{\varepsilon}_1\right)}, \quad (7)$$

$$V_0^{\text{guess}} = \frac{kT\ln\left(\dot{\varepsilon}_2/\dot{\varepsilon}_1\right)}{\widehat{\sigma}_2 - \widehat{\sigma}_2}, \quad (8)$$

respectively.

The third constant $\dot{\varepsilon}_c$ will be determined from the threshold strain rate separating the thermally activated regime from the viscous regime [4]. Denoting $\widehat{\dot{\varepsilon}_t}$ threshold strain rate, the first guess of $\dot{\varepsilon}_c$ is defined as

$$\dot{\varepsilon}_c^{\text{guess}} = 10\widehat{\dot{\varepsilon}_t}. \quad (9)$$

These guesses are then considered as initial values of an optimization procedure of which the cost function is an error defined using the relative difference between the experimental yield stress and the yield stress predicted by (6). More precisely,

$$\sigma_0, V_0, \dot{\varepsilon}_c = \underset{\sigma_0, V_0, \dot{\varepsilon}_c}{\arg\min} f\left(\sigma_0, V_0, \dot{\varepsilon}_c\right), \quad (10)$$

where f is the cost function.

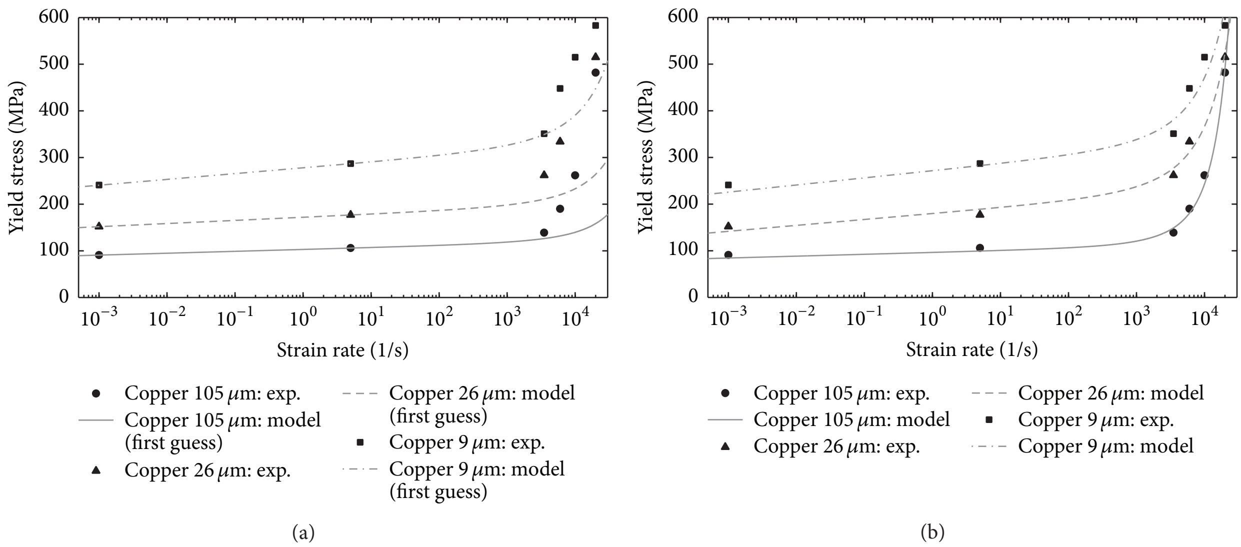


Figure 1: Comparison between experimental data (Couque [4]) and new modified Eyring equation for copper: (a) first-guess material constants and (b) optimized materials constants.

Table 1: Material constants for copper.

	σ_0^{guess} (MPa)	σ_0 (MPa)	V_0^{guess} (nm^3)	V_0 (nm^3)	$\dot{\varepsilon}_c^{\text{guess}}$ (s^{-1})	$\dot{\varepsilon}_c$ (s^{-1})
Copper 105 μm	103	96.4	2.31	2.35	15000	2037
Copper 26 μm	172	179.8	1.39	0.737	15000	5919
Copper 9 μm	278	271.6	0.754	0.612	15000	7163

Table 2: Material constants for A304L steel.

	σ_0^{guess} (MPa)	σ_0 (MPa)	V_0^{guess} (nm^3)	V_0 (nm^3)	$\dot{\varepsilon}_c^{\text{guess}}$ (s^{-1})	$\dot{\varepsilon}_c$ (s^{-1})
A304L 100 μm	336	347.9	0.827	0.376	15000	2946
A304L 10 μm	714	667.5	0.279	0.737	8000	2113

3. Results and Discussion

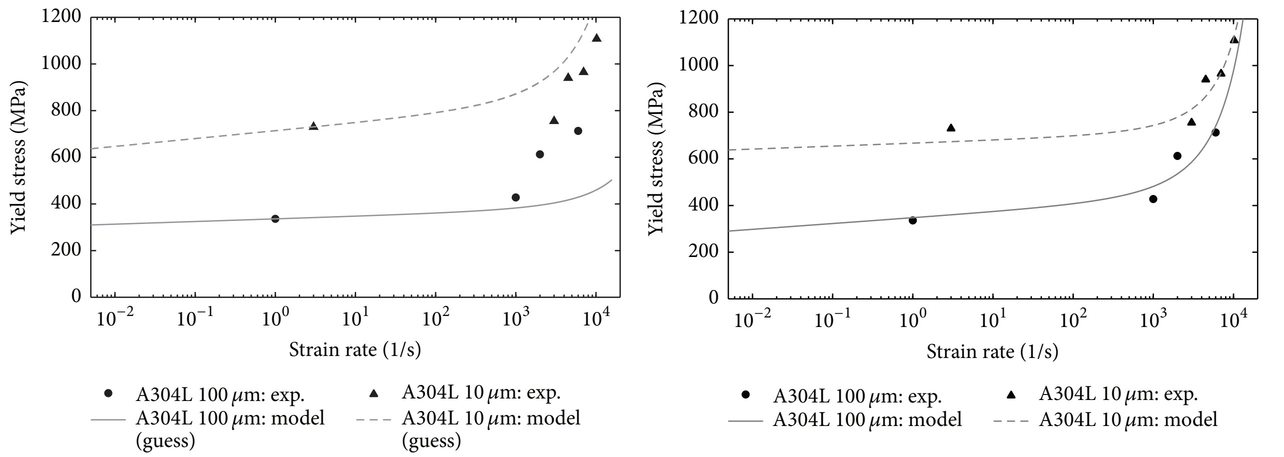
In order to check the applicability of the new constitutive equation and the identification procedure to metals, several metallic materials are considered here. First we consider two materials, namely, copper and A304L steel, to show the quality of the first-guess material constants. Couque [4] has already reported experimental values of copper and A304L steel yield stresses for strain rates up to ~20000/s and ~10000/s, respectively. In order to achieve so high strain rates a direct-impact Hopkinson bar was used [4, 5, 28].

The two-step identification procedure, detailed above, is used to determine the materials constants of (6) for three copper materials and two AA304L steels. The experimental yield stress data are obtained from Couque [4]. The first-guess and optimized material constants are given in Tables 1 and 2. Besides, the experimental yield stress reported by Couque [4] is compared to the yield stress predicted by the new modified Eyring equation (6) in Figures 1 and 2.

Using the first-guess material constants, it is easy to fit the quasi-static and intermediate strain rate data (Figures 1(a) and 2(a)). It is less easy to catch the yield stress increase at high strain rates. This can be linked to the difficulty of giving a close first guess of the critical strain rate $\dot{\varepsilon}_c$. It is difficult to determine exactly the transition between thermally activated and viscous regimes, indeed. However, the first guess is very useful to determine initial values for the optimization problem, which is a crucial and important task. In this work, the first-guess parameters are even more important because they give close values of σ_0 and V_0 (Tables 1 and 2). Thus the optimization procedure will mostly concentrate on refining the value of $\dot{\varepsilon}_c$.

Using the optimized materials constants, the new modified Eyring equation fits well the experimental data (Figures 1(b) and 2(b)). It catches the behavior in the quasi-static as well as high strain rate ranges. The sharp increase of the yield stress at very high strain rates is well predicted up to ~20000/s for three copper materials and up to ~10000/s for two A304L steel materials.

Henceforth, we will concentrate on the results obtained by only the optimized materials constants. The modified Eyring equation is then used to fit the behavior of other metallic materials. Figure 3 compares the flow stress, at 10% of plastic strain, of two aluminum alloys predicted by the new modified Eyring equation to the experimental flow stress reported by Moćko et al. [35]. Equation (6) fits well the strain rate



(a) (b)

Figure 2: Comparison between experimental data (Couque [4]) and new modified Eyring equation for steel: (a) first-guess material constants and (b) optimized materials constants.

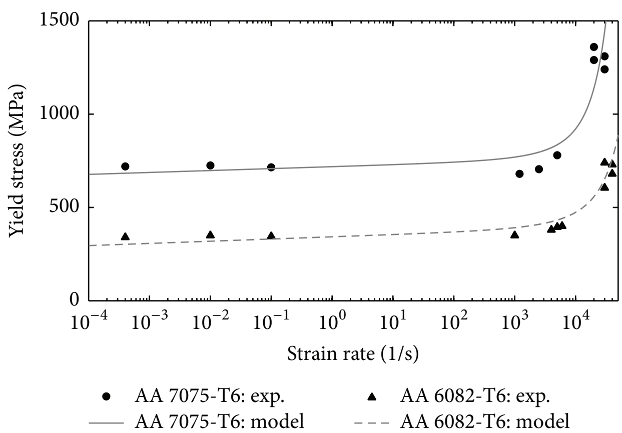


Figure 3: Comparison between experimental data (Moćko et al. [35]) and new modified Eyring equation for aluminum.

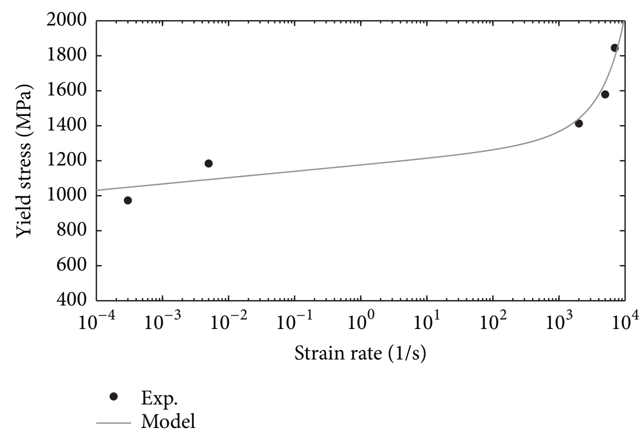


Figure 4: Comparison between experimental data (Subhash et al. [36]) and new modified Eyring equation for CVD textured ⟨011⟩ tungsten.

sensitivity of the two materials, except for the drop in the flow of AA 6082-T6 at around 1000/s, which should rather be attributed to the change of the testing machine as it is an uncommon behavior.

The modified Eyring equation fits well the flow stress at 5% of strain of CVD textured ⟨011⟩ tungsten (Figure 4). The discrepancy obtained at low strain rates could rather be attributed to the unusual important jump of stress between $3 \times 10^{-4}\ \mathrm{s}^{-1}$ and $5 \times 10^{-3}\ \mathrm{s}^{-1}$.

Dealing with temperature effect on the strain rate sensitivity, Figure 5 compares the yield stress of annealed mild steel as predicted by (6) to the yield stress reported in [38]. For the two considered temperatures, that is, 293 and 493°K, the modified Eyring equation fits well the experimental yield stress over a very wide range of strain rates (from 10^{-3} to $5\times10^{4}\ \mathrm{s}^{-1}$). Figure 5 shows the capability of the new equation to catch the behavior for strain rates up to $5 \times 10^{4}\ \mathrm{s}^{-1}$.

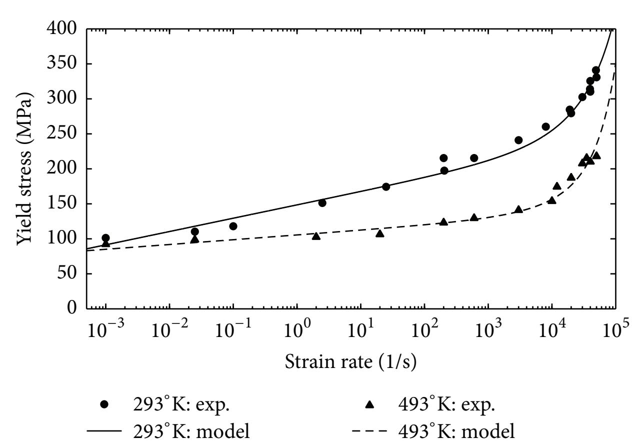


Figure 5: Comparison between experimental data (Clarke et al. [37] and Blazynski [38]) and new modified Eyring equation for annealed mild steel.

TABLE 3: Optimized material constants for several metallic materials.

	σ_0 (MPa)	V_0 (nm^3)	$\dot{\varepsilon}_c$ (s^{-1})
Copper 105 μm	96.4	2.35	2037
Copper 26 μm	179.8	0.737	5919
Copper 9 μm	271.6	0.612	7163
A304L 100 μm	347.9	0.376	2946
A304L 10 μm	667.5	0.737	2113
AA 6082-T6	342.7	0.795	9598
AA 7075-T6	718.6	0.907	3970
CVD textured ⟨011⟩ tungsten	1176	0.258	3158
Annealed mild steel (293°K)	148.5	0.492	89007
Annealed mild steel (493°K)	105.6	1.370	25711
Ti-47Al-2Mn-2Nb alloy (tensile yield)	451.1	0.497	1462
Ti-47Al-2Mn-2Nb alloy (tensile ultimate strength)	481.8	0.495	590
Polyetheretherketone (PEEK) [28]	**159**	**1.01**	**12038**

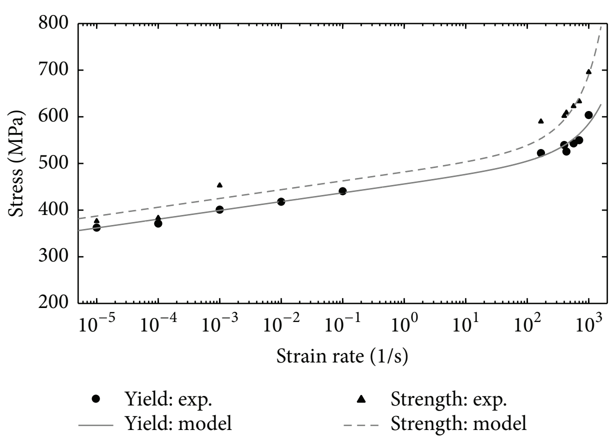


FIGURE 6: Comparison between experimental data (Wang et al. [39]) and new modified Eyring equation for Ti-47Al-2Mn-2Nb alloy.

The last example is dealing with tensile yield and ultimate stress of Ti-47Al-2Mn-2Nb (Figure 6). This example shows that the new equation can also fit the tensile behavior. Moreover, it is shown that it works for strain rates down to 10^{-5} s^{-1}.

The material parameters of the different metallic alloys are synthesized in Table 3. They are also compared to the material parameters obtained for PEEK [28]. It is worth noting that the activation volume V_0 of metallic and polymeric materials is in the same range of [0.25–2.4 nm^3]. This gives a characteristic distance which is in the range of [6–14 Å]. Studying copper over a wide temperature range, Suo et al. [40] reported that the activation volume is in the range of $10b^3$.

Through multiple examples, the new modified Eyring constitutive equation has been showed here to have a great potential to model the strain rate sensitivity of the yield/flow stress over a very wide range of strain rates (from 10^{-5} to 5×10^4 s^{-1}) using only three material constants.

4. Conclusion

In this work, a new modified Eyring constitutive equation, predicting the strain rate sensitivity of yield, was validated regarding the experimental yield stress of several metallic materials. This constitutive equation uses only three material constants which were determined using an optimization procedure. A methodology was established in order to obtain a first guess of the material constants, hence simplifying the optimization step. The modified Eyring equation fits well the experimental data on a very wide range of strain rates (over more than 8 decades). This is highly important result. Indeed, it is possible to fit the yield/flow stress on a so large strain rate range by using only three material constants.

Conflict of Interests

The author declares no conflict of interests.

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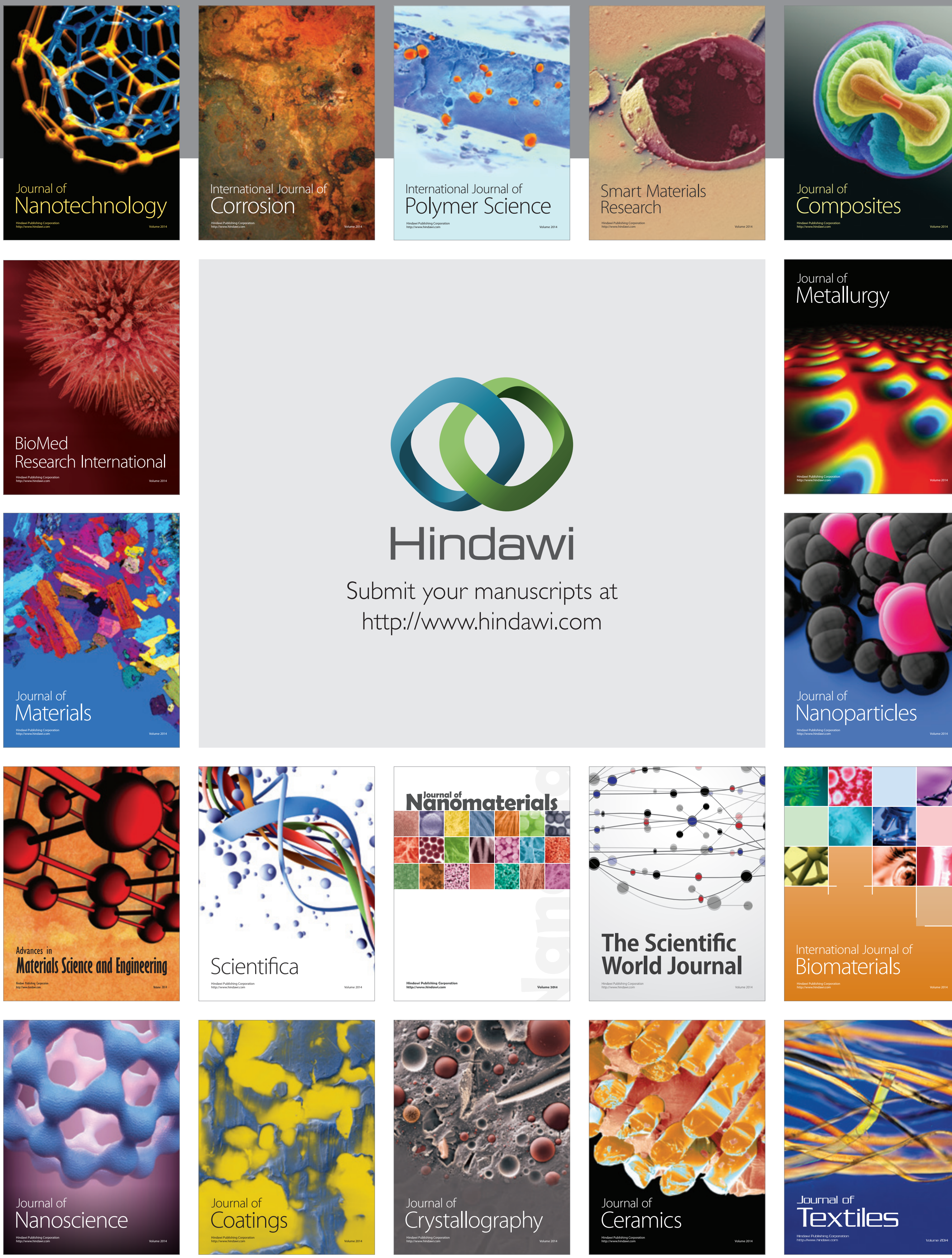
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