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WORK HARDENING BEHAVIOR OF THE Ni-Fe BASED SUPERALLOY IN 718

K.V.U. Praveen, G.V.S. Sastry and Vakil Singh

Centre of Advanced Study, Department of Metallurgical Engineering,
Institute of Technology, Banaras Hindu University
Varanasi – 221 005, (INDIA).

ABSTRACT

Flow behavior of many metals and alloys, in the region of uniform plastic strain, is normally expressed by the simple power law relationship. However, deviations have been observed from such behavior in several fcc metallic materials with low stacking fault energy. Flow behavior of such materials has been expressed by Ludwigson expression. Age hardenable nickel-iron based superalloy (IN 718), is observed to exhibit dual slope plastic flow behavior irrespective of its heat-treated condition. A new approach is made for precise determination of the critical strain (ε_c), to delineate the regions of strain, resulting from planar and cross slip, based on the rate of work hardening.

Keywords: IN 718; work hardening; planar slip; cross slip; critical strain

1. INTRODUCTION

Alloy IN 718 is a precipitation-hardenable nickel-iron base alloy containing mainly chromium, niobium and molybdenum and small amounts of aluminum and titanium. The ease with which this can be fabricated combined with good tensile, fatigue, creep and rupture strength, has resulted in its wide range application. Examples of these are components for liquid fueled rockets, rings, casings and various sheet metal formed parts for aircraft and land based gas turbine engines. The formability of the alloy hence becomes an important factor for the fabrication of such components. Formability of metals and alloys is known to be strongly related to their work hardening behavior.

The simple equation $\sigma = K\varepsilon^n$, where σ is true normal stress and ε is true plastic strain, frequently known as the Hollomon[1] relation has long served as a model for characterization of work hardening behavior of many metals and alloys. However, Low and Garofalo[2] have showed that this relationship is inadequate to describe plastic-flow behavior of the 18-8 stainless steel. Later Ludwigson[3] proposed a modified equation to characterize work hardening behavior of these 18-8 type stainless steels and other fcc alloys with low stacking fault energies. The present investigation is concerned with characterization of work hardening behavior of the superalloy IN 718 at room temperature. It is observed that work hardening behavior of this alloy deviates from the usual power law relationship, irrespective of its heat treated condition. An attempt is made to analyze the tensile data of the alloy 718 in various heat treated conditions, using the different flow relationships such as of Hollomon[1], Ludwik[4], Voce[5], Swift[6] and Ludwigson[3]. C-J (Crussard and Jaoul)[7] analysis of work hardening behavior, in terms of θ ($d\sigma/d\varepsilon$) vs. ε, was carried out for solution treated and three age hardened conditions. The critical strain (ε_c), delineating the region of low and high strain, was determined more accurately from the ($d\sigma/d\varepsilon$) vs. ε curves, rather than using the Ludwigson's approach.

2. EXPERIMENTAL WORK

The material of the present investigation, alloy, IN 718, was supplied by the Project Office (Materials), Kaveri Engine Programme, Defence R&D Organisation, Hyderabad, under the trade name Su 718, in the form of 15mmϕ hot rolled, solution treated and machined bars. The composition of the alloy is given in Table 1. The as received bars were given four different heat treatments viz., solution treatment, peak ageing, over ageing for one hour and over ageing for 100hrs. The details of the heat treatment schedules are given in Table 2. Tensile specimens of 4.54mmϕ and 14.5mm gauge length were machined from the heat treated blanks. Tensile tests were carried out at room temperature using a 50KN screw-driven Instron Universal Testing machine at a constant strain rate of 0.005 s^{-1}.

3. RESULTS AND DISCUSSION

Tensile properties of the alloy in the four different heat-treated conditions are recorded in the Table 3. The log-log plots of true stress vs. true strain are depicted in Figure 1. It is obvious from these plots that the data points of all the three conditions form curves rather than straight lines.

The Hollomon relationship:

$$\sigma = K\varepsilon^n \qquad (1)$$

where σ, ε, K and n are the true stress, true plastic strain, the strength coefficient, and the strain hardening exponent respectively fails to describe the plastic flow behavior of this alloy in all the above heat-treated conditions. The data were analyzed using Hollomon[1], Ludwik[4], Voce[5], Swift[6] and Ludiwigson[3] relationships described in Table 4. The curve fits for the above mentioned relationships are depicted in Figure 2. The effectiveness of a fit is generally indicated by the sum of the residual squares, χ^2, calculated for a given equation. The χ^2 values for the above relationships for the complete range of σ-ε data are given in Table 5. It is evident from there figures that Ludwigson relationship fits well for ST and OA conditions but not for the PA and OA100 conditions, whereas, Ludwik relationship fits best for the PA and OA100 conditions. The failure of the Ludwigson relationship in case of PA and OA100 condition can be understood from the poor correlation (R) between Δ (the deviation of the true stress from extrapolation of the stress corresponding to high strain to low strain region) vs. the true strain (ε) plots (Figure 3). It should be noted that while the other materials exhibiting this kind of a deformation behavior follows the Ludwigson relationship, the material of the present investigation follows Ludwik relationship in PA and OA100 conditions.

The critical strain (ε_c), above which the power law relationship reasonably represents the experimental data, is evaluated for the ST and OA conditions, by setting the ratio (r) of the modified term (Δ), to the power law equation ($K\varepsilon^n$), to some arbitrary small value of 0.02 as suggested by Ludwigson[4].

$$\exp(K_1 + n_1\varepsilon_c) / K\varepsilon^n = r \qquad (2)$$

In case of PA and OA100, which do not follow the Ludwigson relationship, the critical strain is evaluated by differentiating the power law relationship ($K\varepsilon^n$), governing the stress-strain relationship in the high strain region and the Ludwik relationship and then equating them. Thus, ε_c for these conditions is given by:

$$\varepsilon_c = \exp\,[\ln(K_L n_L/Kn)/(n-n_L)] \qquad (3)$$

where, the subscript L represent the Ludwik parameters.

The flow curve parameters for all the conditions are recorded in Table 6. The physical interpretation of these flow curve parameters has been given earlier[8-9]**.** While K expresses the ability of strengthening by deformation, K_1 signifies the short-range stress inducing the movement of first mobile dislocation, n shows the intensity of work hardening, n_1 expresses the rate at which the ratio between the short-range and long-range stress decreases. The critical strain ε_c is the strain below which planar slip is prevalent and above which multiple slip becomes dominant.

The value of the critical strain (ε_c) can be determined more precisely from the plots of the rate of work hardening, ($d\sigma/d\varepsilon$) vs. ε curves. It may be seen that these plots exhibit three distinct regions, in all the four conditions and the point of transition from stage II to stage III gives the critical strain (Figure 4). The values of the critical strain (ε_c), calculated using equations (2) and (3) and that determined from the work hardening plots (Fig. 4) are presented in Table 7. It may be seen that the values of ε_c for the ST and OA conditions, based on the Ludwigson's criterion are higher than those determined from the ($d\sigma/d\varepsilon$) vs. ε plots. However, The value of ε_c for the other two conditions (PA and OA100), determined from equation (3) and from ($d\sigma/d\varepsilon$) vs. ε plots are quite close.

The plots of ($d\sigma/d\varepsilon$) vs. ε for all the four heat treated conditions are shown together in Figure 5. It may be seen that there are three distinct regions in all the cases, however, there is significant variation in stage II. In general it is known that the rate of work hardening continuously decreases with increase in strain, however, deviations from this behavior have earlier been established[10-12]. While the rate of work hardening increases in stage II in ST and OA conditions, it remains nearly constant for the OA100 and decreases slowly for the PA condition. This variation in work hardening behavior of the material in the different heat treated conditions is attributed to the change in the mode of deformation from the region of low strain to that of high strain. Initially deformation occurs relatively easily, as the dislocations can move over relatively large distances before encountering barriers. However, the near free path of dislocations increases in order from PA to OA, OA100 and ST. It is supported from the rate of initial work hardening which is highest for PA and followed in decreasing order by OA, OA100 and ST. After the initial stage of deformation, the deformation behavior of this material varies from that exhibited by the materials following power law relationship, therefore a change in slope. Later on after accumulation of certain amount of deformation, again the deformation mode follows the general mode observed in other materials, as can be seen from the similarity in slopes in stage III to that of stage I. The amount of this strain is what is given by the critical strain (ε_c) term. The ε_c value is found to depend on the n_1 parameter of the Ludwigson's relationship for different materials[3,8-9] irrespective of heat treated condition, temperature and strain rate as can be seen from Figure 6, where all the ε_c values for various material and various conditions exhibit a straight line relationship with $1/n_1$. It implies that the amount of deformation the material undergoes before transforming to the normal mode of deformation depends on the development of short range and long range stresses as explained by Soussan et. al.[8] which in turn depend on the matrix.

4. SUMMARY

The alloy IN 718, exhibits dual slope, in work hardening, in ST, PA, OA and OA100 conditions, at room temperature. While ST and OA conditions follow Ludwigson relationship, PA and OA100 conditions follow Ludwig relationship. The critical strain about which the change in behavior occurs can be determined more precisely using rate of work hardening curves, rather than empirical relationships given by Ludwigson. The rate of work hardening curves shows three distinct regions in all the four heat treated conditions explaining the variation in deformation mode to be responsible for this kind of work hardening behavior.

5. REFERENCES

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TABLES

Table 1. Chemical composition of the as-received alloy 718 bars (wt%).

Ni	Cr	Nb	Mo	Ti	Al	Fe
54.0	18.2	5.01	2.9	1.04	0.54	BAL

Table 2. Heat treatments given to the as-received material.

S.No.	Treatment	Designation	Solution Treatment	Ageing
1	Solution Treatment	ST	980^{o}C/ 1hr/ Water Quenched	-
2	Commercial Ageing	PA	- Do -	720^{o}C/ 8hrs/ Furnace Cool/ 650^{o}C/ 8hrs/ Air Cooled
3	Over Ageing	OA	- Do -	850^{o}C/ 1hr/ Air Cooled
4	Over Ageing	OA100	- Do -	850^{o}C/ 100hr/ Air Cooled

Table 3. Tensile properties of the alloy 718 in the different heat treated conditions.

S.No.	Designation	Yield Strength (MPa)	UTS (MPa)
1	ST	351	847
2	PA	1249	1490
3	OA	660	1079
4	OA100	395	1334

Table 4. Flow relationships relating true stress and true plastic strain.

S.No.	Flow Relationship
1	Hollomon: $\sigma = K_H \varepsilon^{n_H}$
2	Ludwik: $\sigma = \sigma_o + K_L \varepsilon^{n_L}$
3	Voce: $\sigma = \sigma_s - K_V \exp(n_V \varepsilon)$
4	Swift: $\varepsilon = \varepsilon_o + K\sigma^n$
5	Ludwigson: $\sigma = K\varepsilon^n + \exp(K_1 + n_1\varepsilon)$

Table 5. Values of χ^2 obtained for different flow relationships fitted in different heat treated conditions of alloy 718.

S.No.	Condition	Hollomon	Ludwik	Voce	Swift	Ludwigson
1	ST	206024	6108	149576	126783	**2755**
2	PA	31538	**815**	34997	1742	3160
3	OA	110994	46626	109289	83274	**3504**
4	OA100	151846	**845**	181774	138539	1652

Table 6. Summary of the flow curve parameters of the alloy 718, in various heat-treated conditions.

S.No	Designation	K (MPa)	n	K_1	$-n_1$	ε_c
1	ST	2139	0.57	5.76	16.81	0.178
2	PA	1819	0.72	-	-	0.130
3	OA	2161	0.33	5.96	35.90	0.084
4	OA100	1921	0.77	-	-	0.243

Table 7. Critical strain (ε_c), derived from equations (2) and (3) and that obtained through graphical interpretation.

S.No.	Designation	ε_c	
		Mathematical	Graphical
1.	ST	0.178	0.139
2.	PA	0.130	0.132
3.	OA	0.084	0.068
4	OA100	0.243	0.267

FIGURES

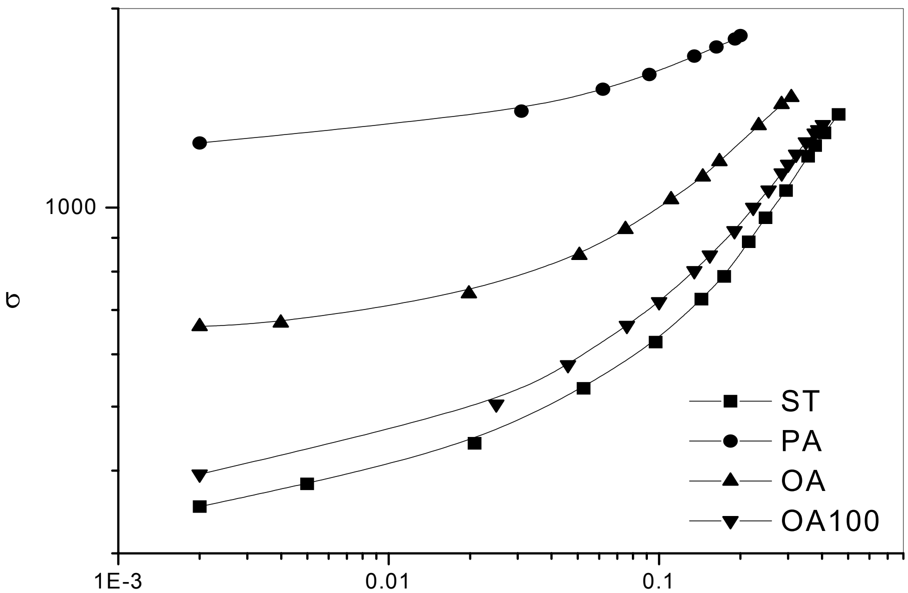

Figure 1. True stress vs true strain plots of the alloy 718 in different heat treated conditions, on log scale.

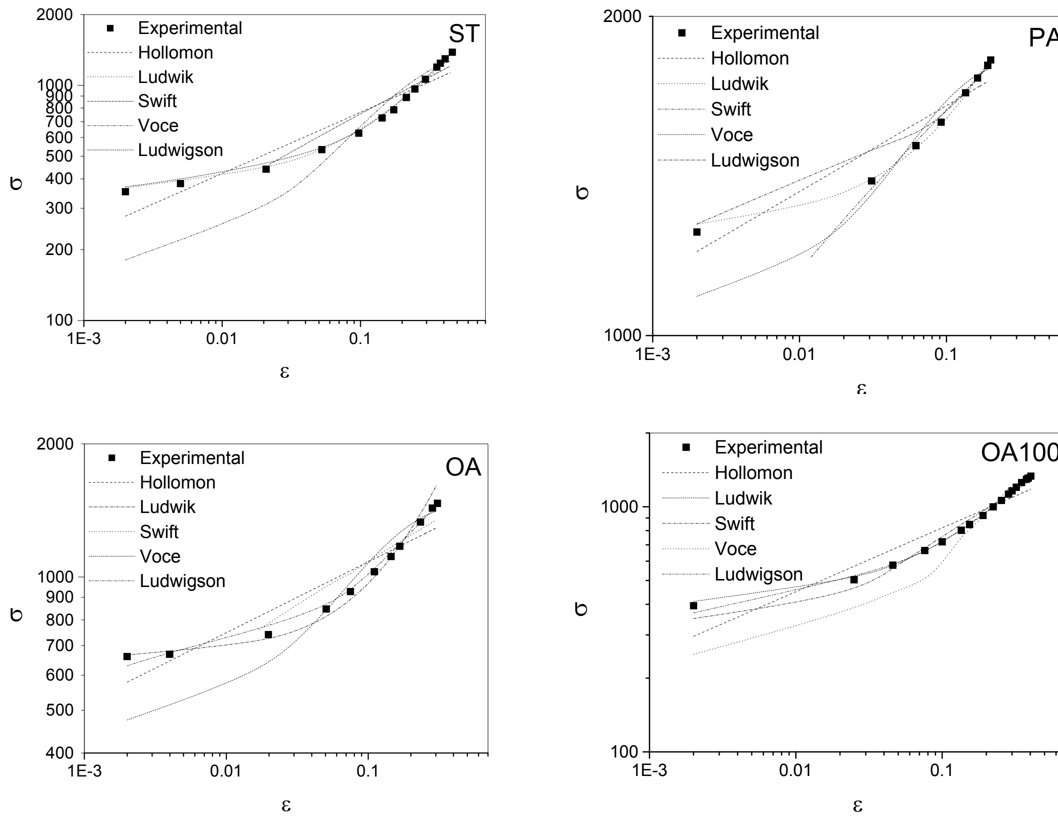

Figure 2. Various curve fittings of true stress vs true strain plots of the alloy 718 in different heat treated conditions, on log scale.

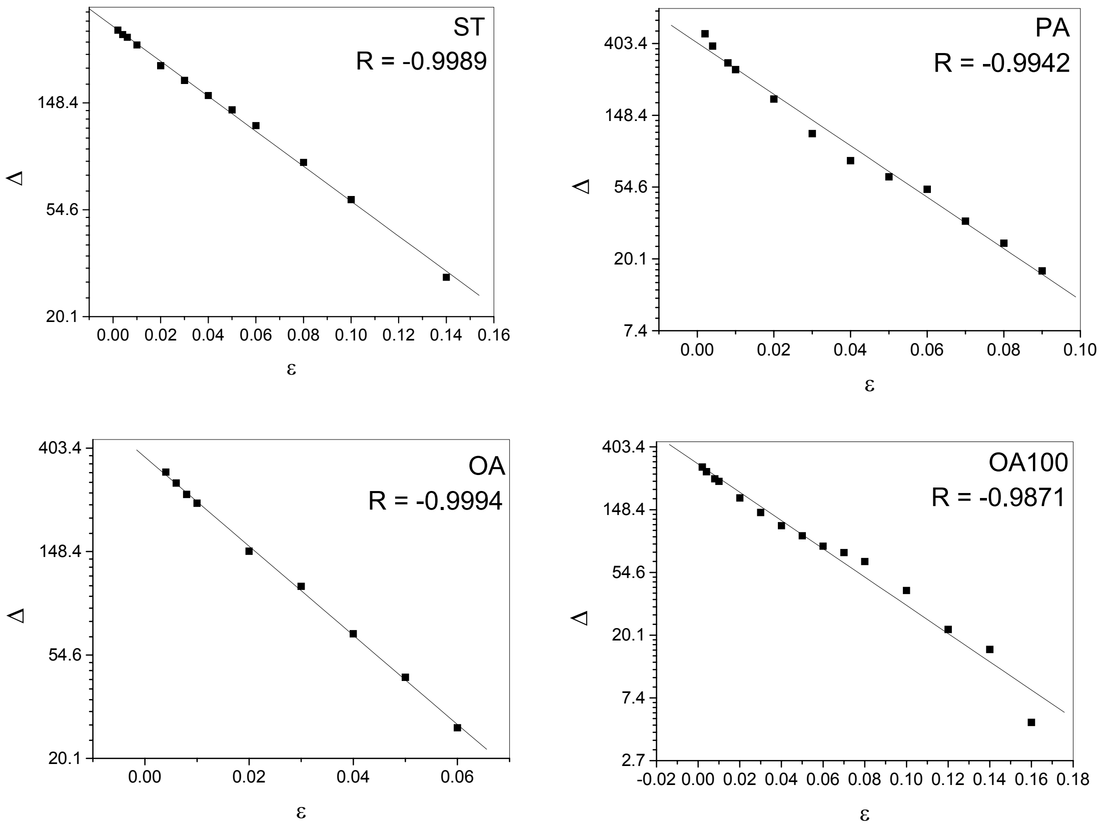

Figure 3. Δ vs. ε plots for different heat treated conditions of alloy 718 for evaluating Ludwigson's parameters

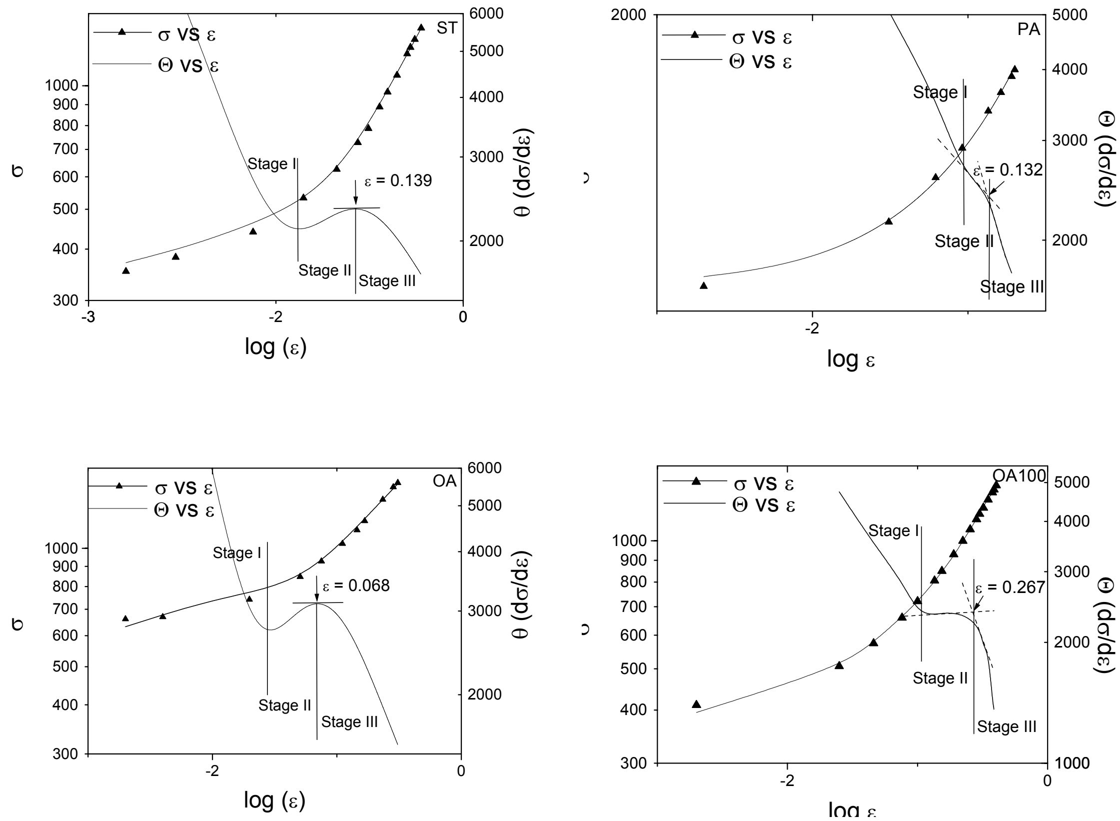

Figure 4. Plots depicting the methodology of determining ε_c from rate of work hardening curves.

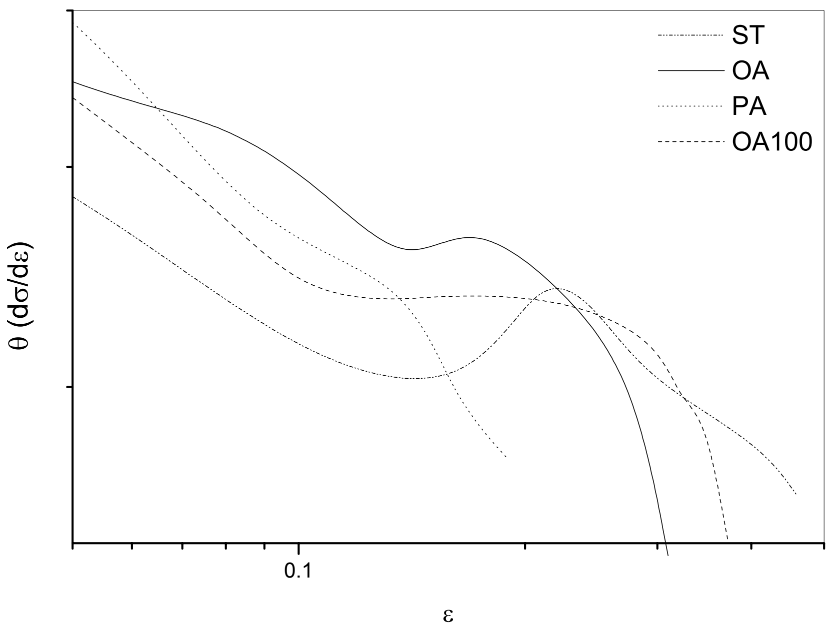

Figure 5. Rate of work hardening (dσ/dε) curves of alloy 718 in different heat treated conditions.

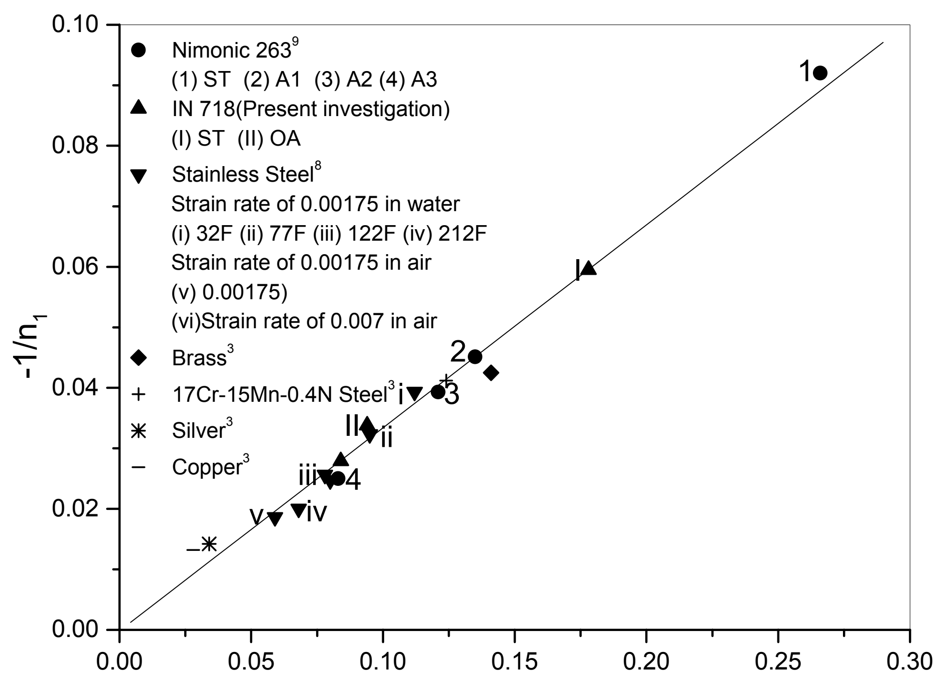

Figure 6. Relationship between $1/n_1$ and ε_c for different materials.