ISSN 1027-5495. Functional Materials, 27, No.1 (2020), p. 93-99.
doi:https://doi.org/10.15407/fm27.01.93

Dynamic mechanical properties of austenitic 304L stainless steel with different strain rates

***Jiao Yufeng*[1], *Hou Yanli*[2]**

[1]Department of Civil Engineering, Henan University of Science and Technology, Luoyang, China
[2]China Qiyuan Engineering Corporation, Xi'an, China

Received November 18, 2019

In this paper, the effects of different strain rate on the tensile mechanical properties of 06Cr19Ni10 austenitic stainless steel 304L at room temperature are studied. The strain rate is divided into a low strain rate range and a high strain rate range. By analyzing the law of nominal stress-strain and real stress-strain under different strain rates, the change law of strain rate sensitivity index, strain hardening strength factor and strain hardening index are obtained. The results show that the elongation and reduction of the area of austenitic stainless steel decrease with an increase of the strain rate. In the region of low strain, the decreasing range is more obvious. The curve of the stress-strain is very close to the nominal one in the low strain rate region. When the strain is greater than 0.021, the stress value increases with the increase of the strain rate. The yield strength increases with the increase of the strain rate. The strain rate sensitive index gradually approaches to zero with the increase of real strain. The hardening index shows a decreasing trend in the region of the low strain rate. The research results of this paper have some value for mastering the dynamic mechanical properties of stainless steel, and can be used to determine and optimize the process parameters of micro stamping.
Keywords: austenitic stainless steel, strain rate, martensite, strain sensitivity index, hardening index.

Исследовано влияние различной скорости деформации на механические свойства при растяжении аустенитной нержавеющей стали марки 06Cr19Ni10 при комнатной температуре. Скорость деформации делится на диапазон низкой скорости деформации и диапазон высокой скорости деформации. Результаты показывают, что с увеличением скорости деформации происходит уменьшение удлинения и площади образцов из аустенитной нержавеющей стали. В области малой деформации диапазон уменьшения более очевиден. Кривая номинального напряжения-деформации очень близка в области низкой скорости деформации. Когда деформация превышает 0,021, значение напряжения увеличивается с увеличением скорости деформации. Предел текучести увеличивается с увеличением скорости деформации. Чувствительный к скорости деформации показатель постепенно приближается к нулю с увеличением реальной деформации. Показатель упрочнения имеет тенденцию к снижению в области низкой скорости деформации. Результаты исследований этой статьи могут быть использованы для определения и оптимизации параметров процесса микроштамповки.

Динамічні механічні властивості аустенітної нержавіючої сталі 304L з різними швидкостями деформації. *Jiao Yufeng, Hou Yanli.*
Досліджено вплив різної швидкості деформації на механічні властивості при розтягуванні аустенітної нержавіючої сталі марки 06Cr19Ni10 при кімнатній температурі. Швидкість деформації ділиться на діапазон низької швидкості деформації і діапазон високої швидкості деформації. Результати показують, що зі збільшенням швидкості деформації відбувається зменшення подовження і площі зразків з аустенітної нержа-

віючої сталі. В області малої деформації діапазон зменшення більш очевидний. Крива номінальної напруги-деформації дуже близька в області низької швидкості деформації. Коли деформація перевищує 0,021, значення напруги збільшується зі збільшенням швидкості деформації. Межа плинності збільшується зі збільшенням швидкості деформації. Чутливий до швидкості деформації показник поступово наближається до нуля зі збільшенням реальної деформації. Показник зміцнення має тенденцію до зниження в області низької швидкості деформації. Результати досліджень цієї статті можуть бути використані для визначення та оптимізації параметрів процесу мікроштамповки.

1. Introduction

Austenitic stainless steel 304L is widely used in engineering because of its good mechanical properties. Because of the instability of austenite, the mechanical properties and microstructure of austenitic stainless steel are different in the process of strain strengthening. The transformation of martensite in metastable austenitic stainless steel also makes the properties of the material instable and the mechanical properties of the material more complex. Moreover, the chemical composition and strain rate will change the lattice state of stainless steel, so that it shows different hardening behavior. Among them, the strain rate is one of the key factors affecting the dynamic mechanical properties of 06Cr19Ni10 austenitic 304L stainless steel [1]. The authors of [2] studied the effect of drawing speed on the tensile properties of SUS stainless steel, and analyzed the changes of microstructure, martensite transformation and temperature during the drawing process. The results show that when the strain rate is less than 0.005 s^{-1}, the transformation occurs in austenitic stainless steel 304L, and the transformation amount increases with the decrease of the strain rate. In [3] the authors studied the strain hardening behavior of 0.1 mm thick stainless steel foil at different strain rates. The results showed that the hardening index increased with the increase of the strain rate at low strain rates, but not at high strain rates. In [4–9], the influence of the strain rate on the tensile mechanical properties of metastable austenitic stainless steel was studied, and the stress-strain curves of stainless steel under different strain rates were obtained; but the constitutive model of material considering the strain rate was not obtained. Based on the tensile test at room temperature, the authors of [10] studied the effect of the strain rate on the hardening behavior of austenitic stainless steel from the strain rate sensitivity index and strain hardening index, and deduced the constitutive model of stainless steel considering the strain rate sensitivity index and strain hardening index to describe the mechanical hardening behavior of austenitic stainless steel; the model is in good agreement with the test. Metastable austenitic stainless steel has the strain rate sensitivity, but Swift, Ludiwik models [11, 12] and other constitutive models fail to consider the effect of strain rate. The model proposed in [13–15] is also complex, which is not suitable for simulation.

Based on the above research, the influence of different strain rate areas on the tensile mechanical properties of 06Cr19Ni10 austenitic stainless steel 304L at room temperature is studied. The strain rate area was divided into a low strain rate range and a high strain rate range. The nominal stress-vs-strain law and true stress-vs-strain law under different strain rates are investigated. Moreover, the strain rate sensitivity index and strain strengthening are also studied. The results of this study have a certain reference value for mastering the dynamic mechanical properties of stainless steel and for determining and optimizing the micro stamping process parameters.

1. Experimental

1.1 specimen design

To assess the effect of different strain rate on the material characteristic, tensile specimens of 06Cr19Ni10 austenitic stainless steel were taken in the rolling direction. The specific dimensions are shown in Fig. 1, with a gauge length of 50 mm and a thickness of 1.0 mm. The main chemical composition is shown in Table 1.

1.2 Test parameters

Eight different quasi-static displacement velocities were selected: 0.00033 s^{-1}, 0.0005 s^{-1}, 0.0016 s^{-1}, 0.0033 s^{-1}, 0.005 s^{-1}, 0.017 s^{-1}, 0.05 s^{-1}, and 0.15 s^{-1}. The corresponding experiments are numbered from 1 to 8 in turn. Three samples were taken from each group and the average value was taken as the data for analysis. The extensometer with a gauge distance of 25 mm was used to control the test, and the control accuracy was 0.01 %. During the test, two ends of the test piece are tightened with wedge clamps, the lower end is fixed, and the

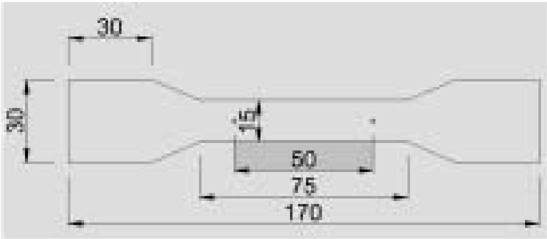

Fig. 1. The geometry of tensile specimen.

Table 1. Chemical composition of 06Cr19Ni10 austenitic stainless steel (wt.%)

C	Mn	P	S	Si	Cr	Ni
0.079	2.00	0.045	0.030	0.98	18.0 ~ 20.0	8.0 ~ 11.0

upper end is subjected to the unidirectional tensile test at the displacement speed set above.

2. Results and discussion

2.1 Reduction of area

The reduction of area ψ of the test specimen is calculated by equation (1)

$$\psi = \frac{A_0 - A}{A_0} \cdot 100\% . \quad (1)$$

Here, A_0 is the original cross-sectional area of the material; A is the cross-sectional area after the material is broken. Table 2 shows the reduction of the area of the test specimen, and the corresponding change diagram is shown in Fig. 2.

As shown in Fig. 3, the reduction of the area decreases with the increase of the strain rate. When the strain rate is less than 0.005, the reduction degree of the reduction rate is greater than that for the high strain rate. When the strain rate is high, the reason for the decrease of shrinkage is that the plastic strain is small; namely, the larger the strain rate, the less plastic deformation. On the contrary, when the strain rate is low, the amount of martensite transformation is small, which leads to the formation of non-uniform deformation, resulting in the rapid decline of shrinkage.

Table 2. Reduction of the area of test specimens at different strain rates

No.	Strain rate, s^{-1}	Reduction of area, %
1	0.00033	5.68
2	0.0005	5.12
3	0.0016	4.16
4	0.0033	3.89
5	0.005	3.74
6	0.017	3.56
7	0.05	2.99
8	0.15	2.87

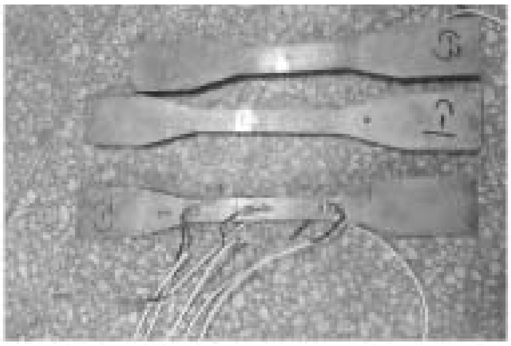

Fig. 2. Photo of the specimens.

Table 3. Elongation of test specimens at different strain rates

No.	Strain rate, s^{-1}	Elongation, %
1	0.00033	19.14
2	0.0005	18.87
3	0.0016	17.59
4	0.0033	16.95
5	0.005	16.16
6	0.017	15.03
7	0.05	14.69
8	0.15	13.97

2.2 Elongation results analysis

The elongation of the test specimen can be calculated by equation (2)

$$\delta_s = \frac{L_s - L}{L_0} \cdot 100\% , \quad (2)$$

Here L_0 is the gauge length, L_s is the length of the test piece after being pulled off. Table 3 shows the elongation at different strain rates, and Fig. 4 shows the corresponding line chart.

It can be seen from Fig. 4 that the elongation of the specimen decreases with the increase of strain rate. In the region of the low strain rate, the rate of elongation decrease is faster. With the increase of the strain rate, the martensitic transformation is more and more inadequate, and the inhomogeneous deformation is smaller, so the elongation of the material is also reduced gradually. When the strain rate is higher than 0.0017, the decrease of elongation tends to be gentle, and the transformation

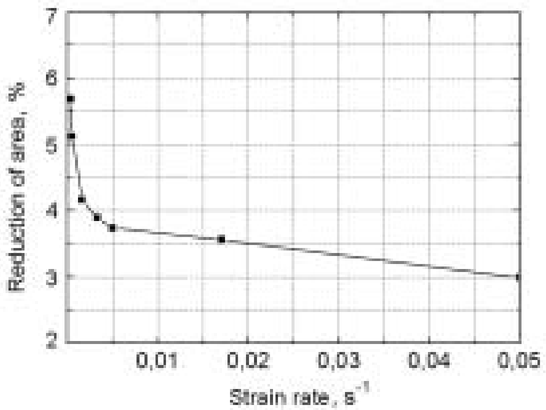

Fig. 3. Relationship between strain area reduction and strain rate of specimens after fracture.

of martensite has little effect on the change of elongation.

2.3 Nominal stress-strain curves

Figure 5 shows the nominal stress-strain curves at different strain rates. It can be seen from the figure that when the strain is less than 0.021, the nominal stress-strain curves at all the strain rates are very close. When the strain is greater than 0.021, the stress increases with the increase of the strain rate. When the strain rate is small, the ultimate strain is also small. And when the strain rate is 0.15, the ultimate strain reaches 0.6.

When the strain rate increases, the yield strength becomes larger. The reason is that with the increase of the strain rate, the dislocation movement becomes relatively difficult, and work hardening is more serious, so the yield strength increases accordingly.

Figure 6 shows the yield stress and tensile strength curves as a function of strain rate. It can be seen from the figure that the tensile strength and yield strength of 06Cr19Ni10 austenitic stainless steel 304L are about 867 MPa and 389 MPa, respectively. In the region of low strain rate, the yield strength increases with the increase of strain rate. The main reason is that 304L stainless steel is a kind of low stacking fault energy metal. If the deformation is accelerated, the crystal is easy deformed, the work hardening accelerate leading to the increase of yield strength. In addition, the reduction of the strain rate makes the martensite transformation more efficient, and the load acting on austenite will be transferred to martensite, so that the uneven deformation will not occur early. Therefore, the tensile strength will be improved.

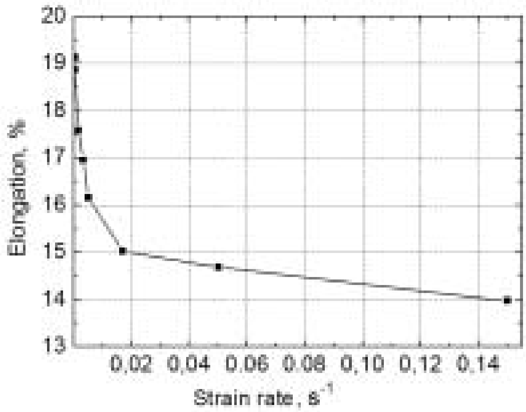

Fig. 4. Relationship between elongation and strain rate.

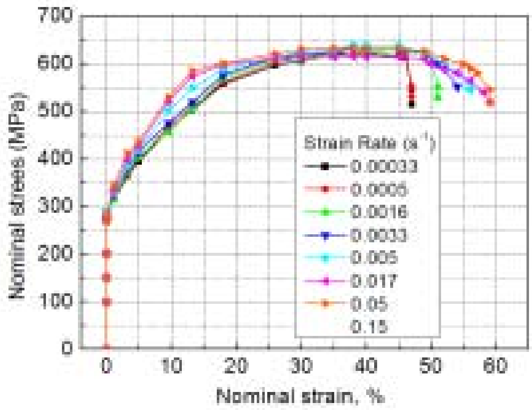

Fig. 5. Nominal stress-strain curves.

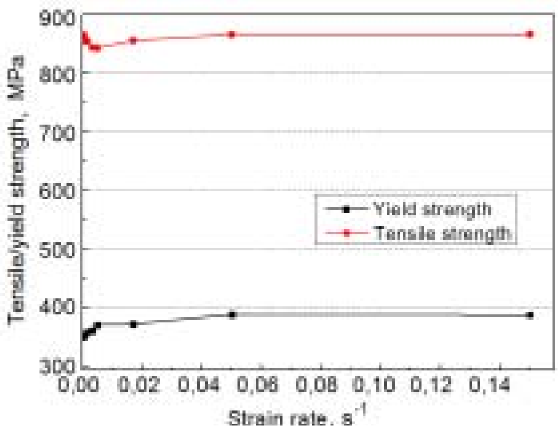

Fig. 6. Yield strength and tensile strength.

2.4 True stress-strain curves

Engineering stress and engineering strain are obtained by dividing the force and deformation measured in the test by the corresponding original cross-sectional area and original gauge distance of the standard test specimen. When the elastic deformation of the specimen occurs, it enters the stage of uniform plastic deformation. With the elongation of the specimen, the cross-sec-

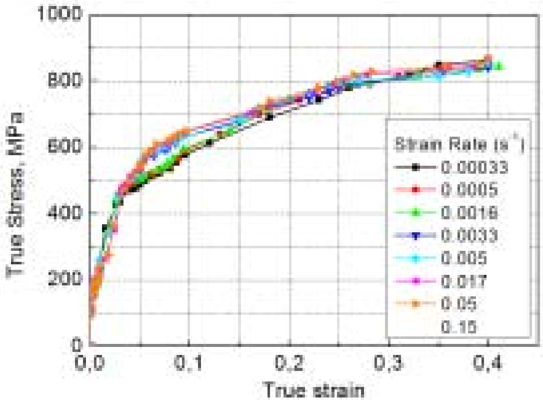

Fig. 7. True stress-strain curves.

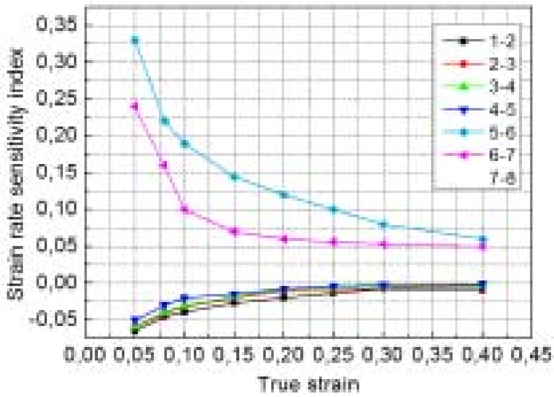

Fig. 8. Strain rate sensitivity index-true strain.

tional area becomes smaller. When entering the stage of local plastic deformation, the cross-sectional area changes significantly. At this time, the true stress of the test piece is significantly higher than the engineering stress, and the true strain is lower than the engineering strain. Therefore, in this paper, the test results are transformed into the true stress-strain curve for analysis and research, and the transformation is carried out through formula (3). The real stress-strain curve obtained from the transformation is shown in Fig. 7.

$$\varepsilon_T = \ln(1 + \varepsilon), \quad \sigma_T = \sigma(1 + \varepsilon). \tag{3}$$

It can be seen from Fig. 7 that with the increase of stress variables, the true stress-strain curve tends to be consistent gradually to the nominal one, and the stress difference becomes smaller and smaller. The reason is that when the strain rate increases, the tensile speed increases, which causes the martensite transformation to be slower than that at slow tensile rate. So that the real speed of the stress increase gradually slows down, resulting in the stress value gradually equal with the increase of load.

2.5 Analysis of strain rate sensitivity index

The relationship between the strain rate sensitivity index and true strain of the stainless steel is shown in Fig. 8. In this case, the definition of the strain rate sensitivity index is expressed by formula (4).

$$\beta = \frac{\partial \ln\sigma / \partial \ln\varepsilon}{\varepsilon}. \tag{4}$$

Here β is the strain rate sensitivity index, ε is the true strain and σ is the true stress. It can be seen from the definition that the closer the β value to zero, the less the sensitivity of the mechanical hardening to the strain rate. According to the formula of the strain rate sensitivity index, the relationship between the strain rate sensitivity index and the true strain can be obtained, as shown in Fig. 8. Among them, 1–2 means the strain rate ranges from 0.00033 to 0.0005; 2–3 means the strain rate ranges from 0.0005 to 0.0016. That is, the number of strain rates, as shown in Table 2, and so on.

It can be seen from Fig. 8 that the strain rate sensitivity index gradually approaches to zero with the increase of the real strain. In the low strain area, i.e. when the strain rate is less than 0.005, the range of change of the strain rate sensitivity index is small, and the sensitivity of the tensile mechanical properties of austenitic stainless steel to the strain rate decreases. When the strain is 0.30, the strain rate sensitivity index is close to zero; in the high strain region, that is, when the strain rate exceeds 0.017, the absolute value of the rate sensitivity index is large, and the curve changes greatly, so the strain rate has a great influence. In the high strain region, the minimum value of sensitivity index is 0.05.

2.6 Analysis of strain hardening strength factor

From the true stress-strain curve of stainless steel, it can be seen that stainless steel shows a plastic hardening behavior. In this regard, Ludwigson et al. [16] proposed that the plastic behavior in the high strain region can be described by Ludwik's equation, and the true strain and stress corresponding to the transition region can be described by formula (5).

$$\sigma_L = K\varepsilon_L^n, \tag{5}$$

Table 4. Results of hardening parameters

No.	Strain rate, s^{-1}	K	n	ε_L	σ_L, MPa
1	0.00033	1517.2	0.7012	0.236	551.2
2	0.0005	1319.39	0.5963	0.225	542.1
3	0.0016	1289.49	0.5514	0.211	546.8
4	0.0033	1273.00	0.5321	0.199	539.2
5	0.005	1303.81	0.5541	0.208	546.2
6	0.017	1381.18	0.6023	0.217	550.3
7	0.05	1377.77	0.6115	0.227	556.4
8	0.15	1461.99	0.6533	0.231	561.3

where K is the strain hardening strength factor and n is the hardening index, σ_L is transient stress and ε_L is transient strain.

Through the "true stress-true strain" relationship obtained from the test, the strain hardening strength factor and hardening index can be calculated under different strain rates, as shown in Table 4 and Fig. 8. It can be seen from Table 4 and Fig. 9 that the hardening index shows a decreasing trend in the area of low strain rates, reaching the lowest value of 0.5321 at the strain rate of 0.0033. When the strain rate exceeds 0.0033, the hardening index shows an overall upward trend. The main reason is that in the static tensile stage, the increase of strain rate will cause the martensite transformation and then increase the work hardening, so that the hardening index increases with the increase of strain rate. The change of the hardening index is related to the change of the strain rate.

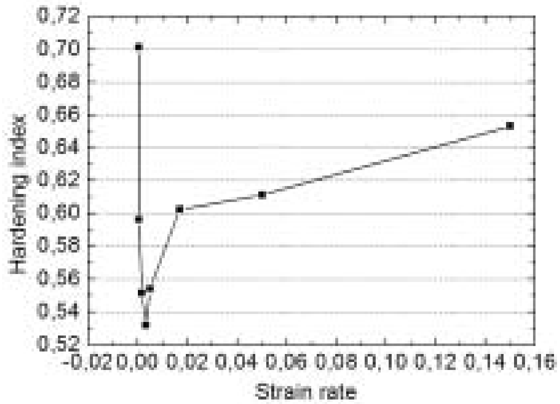

Fig. 9. Strain rate-hardening index.

3. Conclusions

The strain rate has a great influence on the tensile properties of austenitic stainless steel. The elongation and reduction of area of stainless steel specimens decrease with the increase of the strain rate. In the region of low strain, the decreasing range is more obvious. The reason is that when the strain rate is low, the amount of martensite transformation is small, which leads to the formation of non-uniform deformation, resulting in the rapid decline of shrinkage.

The curve of stress-strain dependence in the low strain rate region is very close to the nominal one. When the strain is greater than 0.021, the stress value increases with the improvement of the strain rate. The yield strength increases with incresing the strain rate. The reason is that with the increase of the strain rate, dislocations movement becomes relatively difficult, and work hardening is serious, so the yield strength increases accordingly.

The strain rate sensitivity index gradually approaches to zero with the increase of real strain. In the low strain region, i.e. when the strain rate is less than 0.005, the strain rate sensitivity index changes less; when the strain is 0.30, the strain sensitivity index approaches zero; in the high strain region, i.e. when the strain rate is more than 0.017, the absolute value of the rate sensitivity index is larger and the curve changes more, so the strain rate has a great influence. In the high strain region, the minimum value of sensitivity index is 0.05, which is higher than that in the low strain rate region.

The hardening index shows a decreasing trend in the region of low strain rate. When the strain rate exceeds 0.0033, the hardening index shows an overall upward trend. The main reason is that in the static tensile stage, the increase of the strain rate causes the martensite transformation, and then the work hardening increases, so that the hardening index increases with the increase of the strain rate. The change of the hardening index is related to the change of the strain rate.

References

1. Bian Hongxia, Zhu Liang, Tu Peng, *Hot Work.Technol.*, **44**, 142 (2015).
2. Ye Liyan, Li Xifeng, Chen Jun, *J. Plasticity Engin.*, **20**, 89 (2013).
3. Liu Xiu, Jin Xia, Lou Hangfei et al., *Mater. Sci. Techn.*, **27**, 5 (2019).
4. A.Joshua, C.Martin, J.Chester, *Metall. Mater. Trans. A*, **37**, 147 (2006).
5. A.A.Lebedev, V.V.Kosarchuk, *Intern. J. Plasticity*, **16**, 749 (2000).
6. J.Post, H.Nolles, K.Datta et al., *Mater. Sci. Engin. A.*,**498**, 179 (2008).
7. Arpan Das, Soumitra Tarafder, *Intern. J. Plasticity*, **25**, 2222 (2009).
8. S.Curtze, M.Hokka, P.Peura et al., *Mater. Sci. Engin A*, **507**, 124 (2009).
9. J.Talonen, H.Hanninen, *Acta Mater*, **55**, 6108 (2007).
10. Jiang Minzhu, Gong Hongying, Song Chunyu et al., *Hot Work. Technol.*, **7**, 87 (2017).
11. W.Swift, *J. Mech. Phys. Solids*, **1**, 1 (1952).
12. P.Koc, B.Stok, *Comp. Mater. Sci.*, **31**, 155 (2004).
13. J.F.Ganghoffer, K.Simonsson, *Mech. Mater.*, **27**, 125 (1998).
14. J B Leblond, J Devaux, J C Devaux, *Intern. J. Plasticity*, **5**, 551 (1989).
15. F D Foscher, G Reisner, E Werner et al., *Intern. J. Plasticity*, **16**, 723 (2000).
16. D.C.Ludwigson, *Metallurg. Trans.*, **10**, 2825 (1971).