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WEAR BEHAVIOR OF INCONEL 925 ALLOY AFTER PLASTIC DEFORMATION

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Abstract: For orthopedic implant applications, the two main properties of a biomaterial: chemical reactivity and mechanical strength, are of great importance. Therefore, metallic biomaterials have a high utilization rate due to their superior mechanical properties. Inconel 925, a metallic alloy, is widely used in the aerospace and automotive industries, nuclear power plants, gas turbines, etc., where high-temperature strength and oxidation resistance are required. To increase its widespread use in the field of health (such as orthopedic implants, medical devices, and surgical instruments). It is aimed at improving the microstructure and mechanical properties of Inconel 925 alloy. For this purpose, 30%, 50%, and 70% deformation hardening were applied to the alloys through extreme plastic deformation. Microstructural changes such as phase transformations, grain boundaries, and size were investigated by characterization methods. The mechanical properties of the alloy were investigated by micro-hardness and wear tests. A very fine-grained microstructure with a grain size of 0.08μm was obtained for Inconel 925 alloy. The hardness of the alloy was increased by 69% with 339 HV. The best wear resistance was obtained in the 70% deformed sample with 0.548μ.
Keywords: biomaterial, inconel 925 alloy, plastic deformation, wear, rolling.

1. INTRODUCTION

Today's technological developments have produced superalloys with high mechanical properties to obtain technically special materials [1]. Superalloys are generally divided into three main groups according to the elements they contain: nickel-based, iron-nickel-based, and cobalt-based superalloys [2]. While Inconel 925, a nickel-based superalloy, is not as widely used as other Inconel series alloys (600, 625, and 718), it is an unstabilized austenitic stainless steel with low carbon content [3]. Its chemical composition offers high levels of strength and corrosion resistance. This nickel-alloy material, which is mainly composed of nickel, chromium, copper, and molybdenum, is resistant to highly corrosive environments. Inconel 925, a metallic biomaterial with superior strength and high corrosion resistance [4], is a highly-preferred superalloy due to its low density and high strength-to-weight ratio as well [5,6]. In the selection of superalloys for any application field, mechanical properties such as strength and surface stability have to be taken into consideration. As such, a suitable chemical composition and a fine-grained microstructure are desired to increase low-temperature tensile strength. The diversity of sectoral use of superalloys includes aircraft and industrial gas turbines, rocket engines, the chemical industry, the biomaterials sector, and petroleum facilities [7], and is increasing day by day. Scanning electron microscopy (SEM), optical microscope analysis, and X-ray diffraction (XRD) analysis were carried out to investigate the phases formed in the structure after boronizing of Inconel 718 alloy, a nickel-based superalloy, to be used as a biomaterial [8]. The characterization tests showed that the microstructure improved thanks to the formation of coating layers composed of Ni_2Si, Ni_4B_3, and FeB phases. Comparing the creep characteristics and the evolution of the microstructure of Inconel 718 produced by selective laser melting (SLM) with that of the same material produced by forging, Inconel 718 produced by SLM was reported to have shown a weaker creep resistance and plasticity [9].
Inconel 718 super alloy was joined by the GTA welding method using 3 different filler wires, ERNiCu-7, ERNiCrCoMo-1, and ERNiCr-3.The changes in the mechanical properties were investigated by applying the aging heat treatment of the post-weld materials.
As a result of this study, it was determined that there was a decrease in tensile strength and impact strength in all samples [10]. The effects of temperature, particle impact angle, and nitration hardening of Incoloy 718 alloy after solid particle erosion were investigated. The effect of surface hardening by nitration has been noticed that the erosion behavior of nitrided samples is characteristically the same as that of the original samples. However, the

nitration process did not show the expected effect on the material. Even if an increase in hardness was achieved with nitration compared to the original material, it increased the erosion rate because the hardness value of the abrasive particles was higher [11]. The powder mixtures obtained by using commercial In718 and elemental powders produced by the electric current sintering method were compared with the samples produced by the conventional powder metallurgy method. The microstructure of the samples produced by both methods was characterized with the help of metallographic examinations, microhardness, and corrosion tests consisting of scanning electron microscopy and phase analysis (x-ray patterns, quantitative spot, and linear EDS). From the microscopic examinations of the samples whose post-production heat treatment was performed, it was seen that the sample produced with the ECAS technique had a coarse grain structure. In the sample sintered using commercial powders, it was observed that the grains with a rod-like appearance were homogeneously distributed [12].

Inconel 925, a metallic biomaterial with superior strength and high corrosion resistance, is widely used in the industries that require high-temperature strength and oxidation resistance, such as the aerospace industry, nuclear power plants, gas turbines, ceramic industry, automotive industry, etc. In this study, however, Inconel 925 alloy is intended to be used as a biomaterial in orthopedic implants, medical devices, surgical instruments, etc., by improving its mechanical properties by deformation hardening. The microstructure, i.e., phase transformations, grain boundaries, and grain size, was investigated through characterization methods. As such, this study is aimed at increasing the use of Inconel 925 as an implant material in the field of health by ensuring that its superior properties are maintained and further improved after plastic deformation. To improve the mechanical properties of the Inconel 925 sample, deformation hardening was applied to the sample in the warm state with 30%, 50%, and 70% deformation by rolling, then its microstructure was examined to determine the amount of plastic deformation. In this way, the mechanical properties of the Inconel 925 alloy (toughness, ductility, brittleness, yield point, hardening, and fracture points) were improved as a result of deformation hardening at different ratios. Thus, implants produced from this alloy material are expected to be preferred more in the biomedical field. In light of the findings of this study, a patient to whom an implant produced of this material is applied would gain advantages in terms of longer service life, like 25-30 years, and not being exposed to a medical application for the replacement of the implant.

2. MATERIALS AND METHODS

2.1. Deformation method

Inconel 925 used in this study was supplied in the form of an ingot bar and four specimens with a radius of 8mm and a height of 7mm were prepared for use in the experiments. Stress relief annealing was carried out to remove the stresses caused by casting. The phase diagram of Inconel 925 was analyzed and the melting temperature (Tm) was determined to be 1330 °C [12]. According to the temperature-time combination, Inconel 925 was subjected to stress relief annealing at 800 °C for 3 hours. Cooling after stress relieving was carried out by air cooling [13]. With stress relief annealing, the mechanical properties that the material has from production were maintained, but the residual internal stresses were relieved.

The preheating time for Inconel 925 before the extreme plastic deformation by rolling was determined to be 12 minutes [14]. Each specimen was heated at 500°C for 12 minutes in a laboratory-type furnace and made ready for deformation. To deform the specimens by 30%, 50%, and 70%, the respective acting crushing forces on the rolls were calculated by Equation 1. Equation 1 is an empirical statements (σ_{ort} is average stress W_0 is width and L is lenght of sample).

$$F = 1.15 \text{ x } \sigma_{ort} \text{ x } W_0 \text{ x } L \tag{1}$$

Using the above formula, the warm rolling force required for each deformation level was determined [15]. The specimens were deformed using these rolling forces. The first of three specimens were deformed by 30% in a single pass. The second specimen was deformed by 50% in four passes, and the third specimen was deformed by 70% in seven passes. In this way, from four specimens, four samples consisting of one untreated sample and three deformed samples were obtained to be characterized.

2.2. Material characterization

Characterization methods such as SEM-EDS [16,17], were applied after extreme plastic deformation [18]. Metallographic preparation steps (sanding and polishing) were followed to facilitate the examination of microstructures of the untreated and deformed samples. To visualize details, such as grain size and grain boundaries, in an optical examination, 2 ml Nitric Acid (HNO_3): 2 ml Hydrochloric Acid (HCl): 1 ml Hydrofluoric Acid (HF) solution was used. SEM images of the samples after etching were analyzed with a Zeiss Sigma 300 scanning electron microscope (SEM) for the analysis of microstructure, phase, grain size, grain shape, and orientation at a 1µm examination scale. The phase compositions of the samples were determined using the Empyrean X-ray diffraction (XRD) device.

2.3. Micro-hardness Analysis

A Hardway MHVD-1000 IS-type micro-hardness tester was used to analyze the mechanical properties of the samples. It was carried out by dimensional measurement of the impression left on the sample under a 100 kg load applied on the sample for 10 seconds. Deviations in the averages were determined by taking 3 separate measurements from different parts of the sample surface.

2.4. Wear Analysis

Wear analysis was performed using a Bruker UMT wear device. The reciprocating (linear forward-backward) method was used as the wear test method and carried out in a dry environment. The values of testing parameters used in the wear test are presented in Table 1.

Table 1. Experimental Parameters for wear analysis [9].

Alloys	Applied force (N)	Wear distance (m)	Wear time (s)	Velocity (m/s)	Distance (mm)
Untreated and deformed Inconel 925	15	15	1500	10	5

3. RESULTS AND DISCUSSION

3.1. Microstructure Analysis

SEM images of untreated Inconel 925 samples and the samples subjected to extreme plastic deformation by 30%, 50%, and 70%, are given in Figure 1. In general, the samples can be seen to have a γ (gamma) phase structure.
In Figure 1, it is seen that the Inconel 925 alloy elongates in the rolling direction and forms smaller grains that break. To measure the dimensions of these formed grains, the width and length of the original JPG image obtained from the SEM images were measured with the help of a ruler. Then, the size of the grain on the picture was roughly measured with the help of a ruler, and the grain size was determined approximately by dividing the JPG picture by whichever scale size it was.

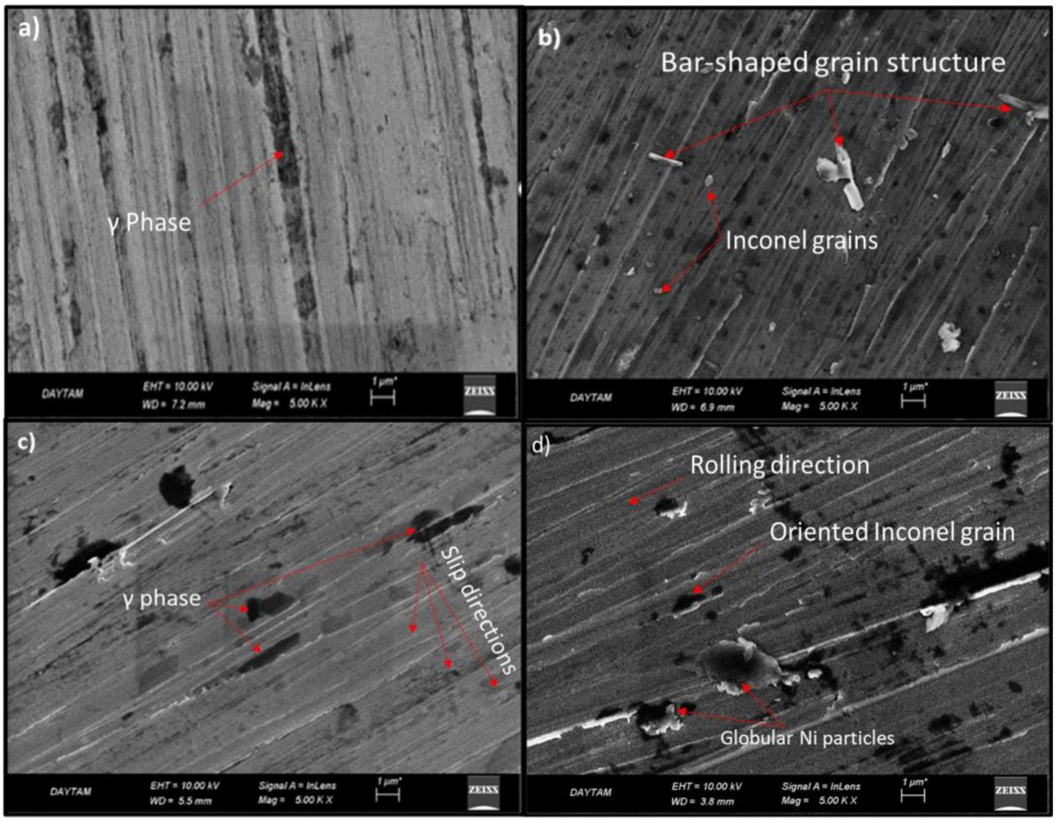

Fig. 1. SEM images (at 1 µm) of Inconel 925 a) untreated and b) 30% deformed c) 50% deformed and d) 70% deformed

The average grain size of untreated Inconel 925 (in Figure 1. a) was 0.4 µm, whereas the grain sizes of Inconel 925 after plastic deformation was determined to be 0.32 µm in 30% deformed sample (Figure 1 b), 0.24 µm in

50% deformed sample (Figure 1 c), and 0.08 µm in 70% deformed sample (Figure 1 d). As the deformation rate increased, the grain size was found to have decreased in the rolling direction, and accordingly, a fine-grained microstructure was obtained [12]. Cr and Ni grains within the superalloy content in the 70% deformed sample show that the γ matrix phase with a face-centered cubic crystal lattice structure was formed. Furthermore, since the slip direction of the grains can be seen clearly, the orientation of the samples can be seen to be in the rolling direction [14, 16, 18]. In the 70% deformed sample which has the highest deformation rate, the grains elongated in the direction of deformation, and an alloy with a very fine grain microstructure of 0.08 µm was obtained, which also brings on an increase in the strength of the alloy.

3.2. Micro Hardness analysis

Micro-hardness measurements, as being a fast method, are important to explicate the effects of plastic deformation on the mechanical properties at the first stage. In this regard, the line chart presented in Figure 2 can help observe the increase in the micro-hardness value of Inconel 925 alloy.

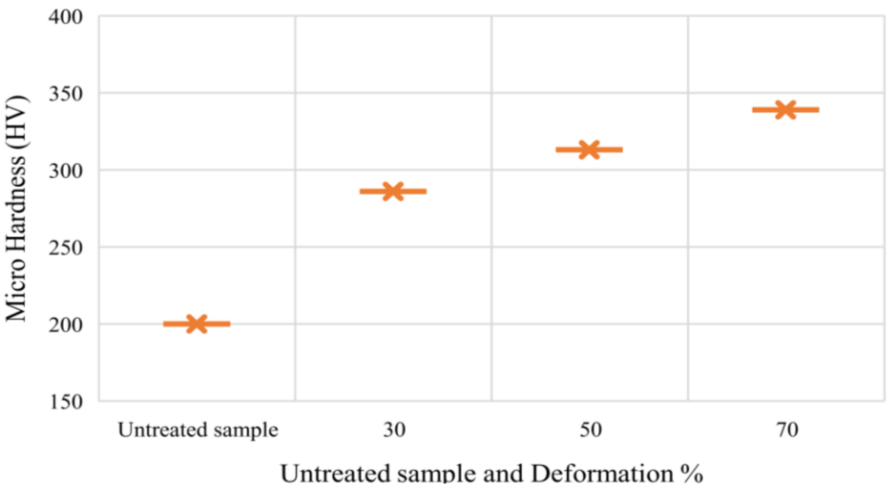

Fig. 2. Microhardness of Inconel 925 alloy

Analyzing the micro-hardness values in the chart, the untreated alloy Inconel 925 can be seen to have the lowest hardness value with 200 HV whereas the highest value was 339 HV in the sample with 70% deformation. It was observed that the hardness value of each sample increased with the deformation rate. It was observed that the hardness value of each alloy sample increased as the deformation rate increased. It is seen that the hardness increase is 43% between the undeformed sample and the 30% deformed sample, 56% in the 50% deformed sample, and 69% in the 70% deformed sample. The average hardness increase of untreated Inconel 925 and 30% 50% and 70% deformed Inconel 925 alloy was determined as 67%.

3.3. Wear test analysis

Applying the wear test with the parameter values presented in Table 1, a total of 1000 data readings were recorded within a period of 1500 seconds (25 minutes) to determine the coefficient of friction of Inconel 925 alloy under a 15 N load. When the friction coefficient-time graph of the alloy is examined in Figure 3, it is seen that the friction coefficient decreases as the deformation rate increases. The highest coefficient of friction is in the untreated sample, while the lowest is in the 70% deformed sample. Using the data in Figure 3, the average friction coefficient value of each alloy was calculated.

Further, the average friction coefficients for the samples are presented in Table 2. When the average coefficient of friction values in Table 2 are examined, the lowest coefficient of friction is 0.548 in the 70% deformed sample, whereas the highest coefficient of friction is 0.653in the untreated sample. Accordingly, the wear was highest in the untreated sample and lowest in the 70% deformed sample. When the average coefficient of friction values in Table 2 are analyzed in terms of deformation rates (i.e., 30%, 50%, and 70%), it is seen that the coefficient of friction decreases with the deformation rate. It can be said that the coefficient of friction in the 70% deformed Inconel 925 sample is considerably lower, especially in comparison to the untreated sample, accordingly the amount of wear can be said to be lowest in this sample. In light of the findings obtained from the wear test, it was determined that increasing the hardness of Inconel 925 would increase the strength of the alloy.

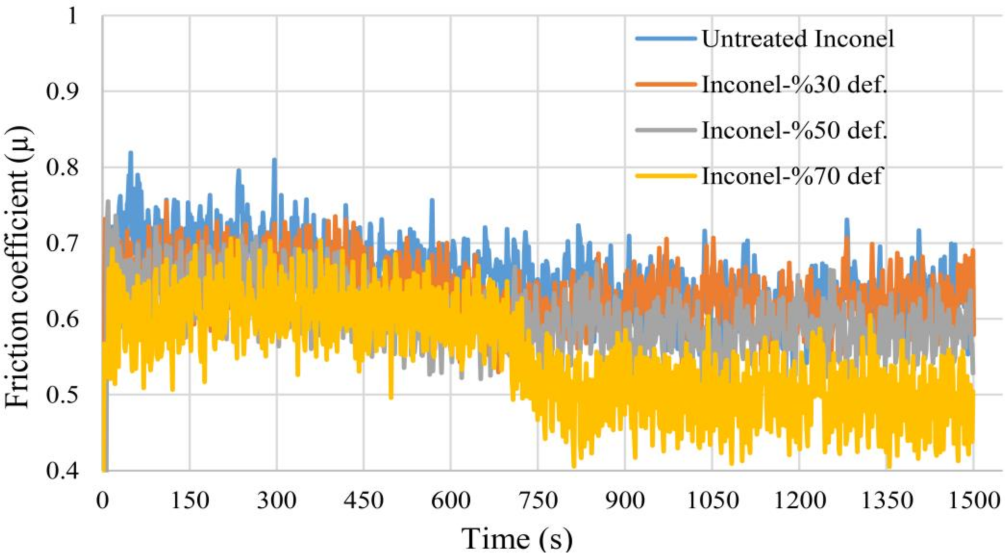

Fig. 3. Friction coefficient-time graph of Untreated and 30.50% and 70% deformed Inconel 925 alloy

The average of reading data was calculated in MS Excel and the average friction coefficients shown Figure 4 were obtained.

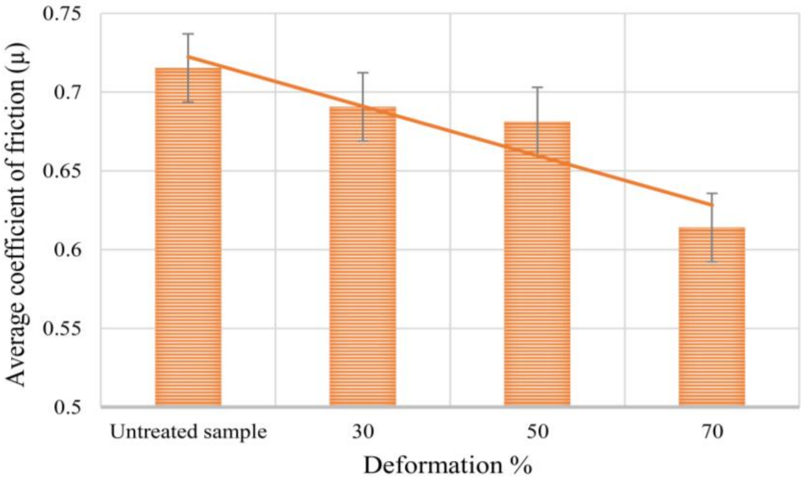

Fig. 4. Coefficient of friction for Inconel 925 samples under 15 N load

Table 2. Variation of average coefficient of friction of untreated and 30%, 50%, and 70% deformed Inconel 925 samples

Sample	Applied force (N)	Velocity (m/s)	Deviation values	The average coefficient of friction (μ)
Untreated	15	10	0.002867	0.715333
30% deformed	15	10	0.003682	0.684333
50% deformed	15	10	0.006236	0.690667
70% deformed	15	10	0.002944	0.614

4. CONCLUSIONS

A study was conducted in which we aimed to increase the use of Inconel 925 alloy as an implant material in the biomaterial sector.
As a result of this study, the hardness value of the alloy, which was plastically deformed by 30, 50% and 70% by the rolling method, increased as the deformation rate increased.
It was observed that the wear resistance of the alloy increased depending on the surface hardness obtained.
In particular, it was concluded that the best abrasion resistance was achieved in the 70% deformed sample.
In this way, the improvement of the wear value, which is one of the mechanical properties of the alloy, will result in a longer life if this alloy is used in implants such as shoulder and kneecaps in the body.
concluded.

REFERENCES

1. Ay, M., (2013). *Investigation of the processability of Inconel 718 nickel alloy with Electro-Thermal processing methods*, Doctoral Thesis, Fırat University Institute of Science and Technology (Elazığ).
2. Ezugwu, E.O., Bonney, J., and Yamane, Y., (2003). *An overview of the machinability of aero-engine alloys*, Journal of Materials Processing Technology, 134, 233-253.
3. Shademan ,S.S., Kim D.S., (2005). *Mechanical and Corrosion Performance of Welded Alloy 925 VIT in Sour Environment*. Corrosion/2005, 05104, 1-20, NACE International, (Houston).
4. Tang C., Bi Z., Du J., and Zhang J., (2014). *Influence of Heat Treatments on Microstructure and Mechanical Properties of Oilfield Used Alloy 925*, Energy Materials, Springer, Cham, 679–685.
5. Kangazian J., Shamanian M., (2017). *Mechanical and Microstructural Evaluation of SAF 2507 and Incoloy 825 Dissimilar Welds*, J. Manuf. Processes, 26, 407-418.
6. Sayiram, G., Arivazhagan, N., (2015). *Microstructural Characterization of Dissimilar Welds Between Incoloy 800H and 321 Austenitic Stainless Steel*, Mater. Charact, 102, 180-188.
7. Vander Voort, G.F., (2004). *Metallography and microstructures of heat resisting alloys*, ASM Handbook V, 9, 1627, ASM International (Ohio).
8. Inanir Z., (2012). *Study of the effect of high operating temperatures on structural and mechanical properties of Inconel 718 alloy*, Master's Thesis, Istanbul Technical University Institute of Science and Technology, (Istanbul).
9. Duran, H., Özkan, D., Karaoğlanli, C., (2021). *Investigation of microstructure, wear, and mechanical properties of Inconel 718 superalloy with boriding treatment*. Karaelmas Journal of Science and Engineering, 11(1), 61-72.
10. Ramkumar, K.D., Kumar, B.M., Krishnan, M.G., Dev, S., Bhalodi, A.J., Arivazhagan, N., Narayanan, S., (2015). *Studies on the weldability, microstructure, and mechanical properties of activated flux TIG weldments of Inconel 718*. Mater. Sci. Eng. A, 639, 234–244.
11. Bircan, B., (2014). *Investigation of solid particle erosion behavior of Inconel 718 alloy*, Master's Thesis, Istanbul Technical University (Istanbul).
12. Ergin, N., (2018). *Production and characterization of Inconel 718 superalloy with electric current-assisted sintering*, Doctoral dissertation, Sakarya University (Sakarya).
13. Demirkol, M., (2010). *Plastic forming technology*, Istanbul Technical University, (Istanbul).https://web.itu.edu.tr/gulmezt/IMAL%20USULLERI/Groover%20PSV%20TUR.pdf
14. Aydogan, I. K., (2007). *Study and modeling of changes in material characteristics in the rolling process, Master's thesis*, Institute of Science and Technology (Istanbul).
15. İşler, A., (1999). *Heat treatment and Mechanical Properties of Titanium alloys*, Doctoral dissertation, Institute of Science and Technology (Istanbul).
16. Leyens C., Peters M., (2006). *Titanium and titanium alloys: fundamentals and applications*, Wiley Online Library.
17. Sujai, S., Ramkumar, K.D., (2020). *Direct aging response on the microstructure and mechanical properties of electron beam welds of Ni-Cr-Fe alloy used in vacuum insulated tubing*, Journal of Manufacturing Processes, 54, 359-373.
18. Kapoor R., (2017). *Severe plastic deformation of materials*, In Materials Under Extreme Condition, 717–754.
19. Kajiwara S., (1986). *Roles of dislocations and grain boundaries in martensite nucleation*, Metallurgical and Materials Transactions A, 17, 1693–1702.

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