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Effect of Martensitic Transformation and Grain Misorientation on Surface Roughening Behavior of Stainless Steel Thin Foils

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Abstract

The surface roughening (Ra), martensitic phase transformation (MPT), grain misorientation(GMO) behavior of stainless steel 304 and 316 were studied by both experimental such as uniaxial tensile stress step by step until five stage and SEM-EBSD investigation. The MPT and GMO after tensile test step by step investigated. The correlation between MPT, GMO, martensitic volume fraction (Mf) and Ra behavior investigated. From the experiment showed that with the increasing strain level from 1,0% to 5,0% affect to the increasing MPT, GMO and Mf transformed from metastable austenitic phase in SUS 304. The increasing strain level affect to the increasing Ra for various grain size (Dg) since fine grain (Dg <3µm) and coarse grain (Dg≥3µm). The reason on using SUS 304 and SUS 316 are to compare the Ra mechanism between SUS 304 and SUS 316 with various Dg. The result showed that the Ra increased both in fine and coarse grain at 1,0% and 5,0% strain level. In coarse grain, the Ra increased significantly proportional, because of low MPT and no GMO in SUS 304 thin foil, no MPT and low GMO in SUS 316 thin foil. Ra increased higher in SUS 304 coarse grain compared to SUS 316 coarse grain thin metal foil. Its indicated that effect of MPT is higher than GMO. In fine grain, Ra increased proportionally to the strain level (εp) because of annealing at 400°C affect to more actively of slip band movement that affect to more inhomogeneous of grain. In the fine grain of SUS 304, the increased of Ra similar both in 1,0 % and 5,0 % strain level, because of similar MPT and GMO both in 1,0 % and 5,0% strain level that affect to the similar of inhomogeneous grain characteristic. The Ra behavior with the same εp and almost the same Dg in SUS 304 and SUS 316 fine grain are similiar, because of grain deformation almost give the same relative inclination between neighboring grain in the direction normal to the surface. Intergrain movement change grain orientation. Based on KAM mapping, the local grain misorientation in SUS 304 is higher than SUS 316. It indicated that in SUS 304 fine grain is harder than fine grain in SUS 316. there is no MPT in SUS 316 because of higher austenitic phase affected by austenitic former such as Ni .

Keywords: Martensitic phase transformation (MPT); Grain Misorientation (GMO); Surface Roughening (Ra).

1. Introduction

Austenitic stainless steel (ASS) has excellent corrosion resistance, processability and widely used in the biomedical, electronic, chemical, electrical power, food and nuclear industry. Beside that, Highly demands for microparts has been received much attention in recent decades. Furthermore, microforming technology have many issues such as the limitation of the material application and requirement of high cost mass production. When the ASS applied plastic deformation, martensitic induced transformation occurred in the ASS. The transformed martensitic volume fraction increase with the increase of plastic deformation.(1-3). Martensitic transformation decrease toughness but increase the strength of ASS (4-5). When subjected ASS with plastic deformation, austenitic stainless steel as metastable phase undergo transformation from FCC austenite to BCT martensite at room temperature. The martensitic transformation might enhance the strength of thin metal foils and elongation. Since an increasing work hardening rate can delay the onset of plastic instability (6). Some factor that affect to martensitic transformations are chemical composition, strain path, grain size, strain level, strain rate.(7-11). Xue et all (12) found that martensitic transformed volume fraction can be controlled by controlling stainless strip steel deformation. Martensitic transformation in the surface is larger than in the inner surface with the same strain. When ASS subjected by plastic deformation, not only martensitic phase transformation (MPT), but also, dislocation interaction and twinning formed. Twinning occur larger in the surface compared to the inner of ASS. The increasing martensitic transformation affect to the increasing stacking fault energy (SFE) of martensite. That why the martensitic transformation in the surface is easier than in the inner. Furthermore, surface roughening also easier to occur in the surface than the inner of thin metal foils. It is need to investigate the correlation between MPT and surface roughening behavior in thin metal foils. Peng et all (13) and z.qin et.all (16) concluded that martensite transformation occur caused by increasing strain rate that affect to the local temperature increase. High increasing strain rate suppresses martensitic transformation. Olson and Cohen model, called OC model, as fundamental work in describing the kinetic of strain induced martensite. Shear band intersection as the dominant nucleation sites is considered. The transformation curve only as function of plastic strain and constant environmental temperature in OC model. Tomita et all (14) found that the number of shear band intersections, which serve as nucleation site, increases as the strain rate increases, while the probability that a shear band intersection forms an embryo is decreased. This conclusion considered only in constant temperature, but for increasing temperature caused by self heating in tensile test was ignored. Zandrahimi et all (15) concluded that transformation of austenite to martensite (MPT) in AISI 304 affect to surface hardening that leading to deterioration of wear resistance. It need to investigate the surface roughness that affected by MPT, because surface roughening caused by grain deformation in the surface and affect to surface properties of thin metal foils. Zihao Qin et all (16), concluded that with the increasing strain rate and temperature the martensitic volume fraction, ultimate tensile strength (UTS) and uniform elongation (UEL) decreased. Jeom et all (17) concluded that strain induced martensitic transformation (SIMT) in duplex stainless steel occurred in sequential manner of austenite→ε martensite appeared when subjected with low strain →α` martensite appeared when subjected with high strain.

However, in metal forming and miniaturization process, the surface roughness ratio of the material to the thickness increase with decreasing sheet thickness, this is called as non uniformity thickness.(18)–(20). Surface roughening phenomena of sheet material will have strong effect on necking, and fracture behavior of materials. The inhomogeneous deformation of each grain located near the free surface will cause the surface roughening phenomena on the free surface of polycrystalline metals. Thus, surface roughening is very important in the field of microforming technology using thin or sheet metal foils. Surface roughening affect to size effect of thin metal foils (21). The material flow and failure behavior of sheet metal with thin thickness are influenced by size effect that is mainly caused by the fewer grains in straining zone (22). Meng et all (23), found that the effect of the free surface roughening on flow behavior and fracture strain is remarkable when the surface non uniformity increases to the same magnitude of sample thickness. Stoudt et all (24), found that the roughening rate was dependent on Mg-Al alloy grain size, and there is linear correlation between roughening rate and grain size. Furushima et all (25), found that the fracture strain of pure copper and pure titanium dramatically decrease from thickness 0,3 mm to 0,1 mm. Thickness strongly affect to fracture strain. Micro metal forming for metal foil with ultra thin thickness has problem on size effect. The ratio of surface roughness to thickness for each material linearly increase with increasing plastic strain. Rabee et all (26), evaluated the relationship between local microstructure and deformation induced surface roughness need to be clarified. Furushima et all (27), concluded that dimple not occur for pure copper thin foils with thickness 0,05mm until 0,1 mm, this means fracture caused by free surface roughening. When the thickness decreased in the same area, the surface roughness increased under uniaxial deformation. It means when the number of grain is decreased, the surface roughness increased, because of uniaxial tensile test with the same strain level. In addition when the quantity of Dg are at least five, the fracture strain is low and the surface roughness significantly increase under uniaxial tensile test with the same strain level. Based on this conclusion, it could be predicted when the grain size (Dg) increase in the constant area, the surface roughness will increase because of uniaxial stress state with the same same strain level. It need to investigate the surface roughening phenomena with different grain size beside copper metal, with thickness at least 0,1µm. Lei Zhang et all (28), found that at present the quantitative description of surface roughness evolution is limited on FCC polycrystalline metals. It need to work beside FCC structure on investigate surface roughening . Kengo Yoshida et all (29), found that the magnitude of surface roughness is mainly governed by the grain size and is less sensitive with ratio thickness to grain size (Ng) and initial thickness. Hence, the thickness imperfection due to surface roughness become large relative to thickness as Ng decreases and need to investigate effect of grain scale heterogeneity on surface roughness and sheet metal necking for material with grain size lower than 10μm. It need to work in thin metal foils with grain size (Dg) below 10µm. Shimizu et all (30) concluded that surface roughening is closely related to the mutual of grains. Thus surface roughness increases due to the different deformation behavior of individual grains. It need to investigate the surface roughness with different Dg that may have misorientation of grain after deformation. Linfa Peng et al (31), found that with the increase of grain size, the individual grains, especially the surface grains, become less restricted due to the decrease of grain boundary density. Considering that the orientation and structures of individual grains are random distributed, the inhomogeneous and uneven deformations of surface grain become more significant, which lead to the increase of surface roughness with the grain size after tensile test. It need to investigate surface roughening phenomena with uniform Dg with different size in thin metal foils.

Furushima et all (32), used pure copper C 10220-O with thickness 0,05mm. It is considered that the weak grain with lower flow stress preferentially deforms with the plastic deformation, which lead to surface roughening. The inhomogeneous deformation of each grain located near the free surface will cause the roughening phenomena on the free surface of polycrystalline metals. There is a chance to work beside C 10220-O focusing on weak and strong grain. P. Groche et al (33), found that decreasing grain size, the flattening of the surface asperities is hindered because of the increase in yield stress due to the hall – petch relationship. Cheng Cheng et al (34), found for the thin sheet metal whose fracture would be due to free surface roughening rather than nucleation and growth of voids inside the material. The free surface roughening is very important in term for understanding mechanical properties of sheet or thin metal foils. Aziz et al (35) found that surface roughening increased proportional in coarse grain of SUS 304 coarse grain indicated by low MPT and no GMO and increase not proportional in fine grain both in SUS 304 and 316 indicated by high MPT and high GMO in SUS 304 thin foil and high GMO in SUS 316 thin foil.

From the previous research, the deformation to the weak grain affect to surface roughening. The increased strain to thin metal foils such as ASS SUS 304 and SUS 316 affect to the increased surface roughness. When the number of grain equal at least five, the surface roughness increased significantly, because of uniaxial tensil stress state. Surface roughness investigation with constant thickness and Dg not yet investigated. The correlation between surface roughness and martensitic phase transformation (MPT) in various Dg still not clear. It can be predicted that if the grain has high of MPT, the grain strength increase and grain deformation become more difficult compared to the grain with lower MPT. The grain with lower MPT become weaker grain compared to the grain with higher MPT. The aim of this study is to clarify how the MPT, GMO affect to grain strength that will be shown by surface roughness behavior of thin metal foils with various Dg. In this study, author use SUS 304 & SUS 316 thin metal foils with various Dg. The reason on using SUS 304 and SUS 316 are to clarify how MPT, GMO affect to surface roughness both in SUS 304 that consist of complicated phase and SUS 316 that consist of more uniform phase with various Dg. From the previous researches, there are not yet research in surface roughening behavior in various thin metal foils with body centre cubic (BCC) and face centre cubic (FCC) structure with different various Dg below 10µm and their phase transformation. First, the purpose of this study is to investigate how the MPT and GMO affect to the surface roughening behavior in SUS 304 and SUS 316 thin metal foils with various Dg. The second purpose is to investigate the effect of fine Dg and coarse Dg to the surface roughening behavior both in SUS 304 and SUS 316 thin metal foils. In this study, ASS SUS 304 and SUS 316 subjected with uniaxial tensile stress state step by step, the surface roughening behavior measured, the MPT, GMO and grain deformation mechanism analysed using SEM-EBSD.

2. Materials and Research Methode

2.1. Materials

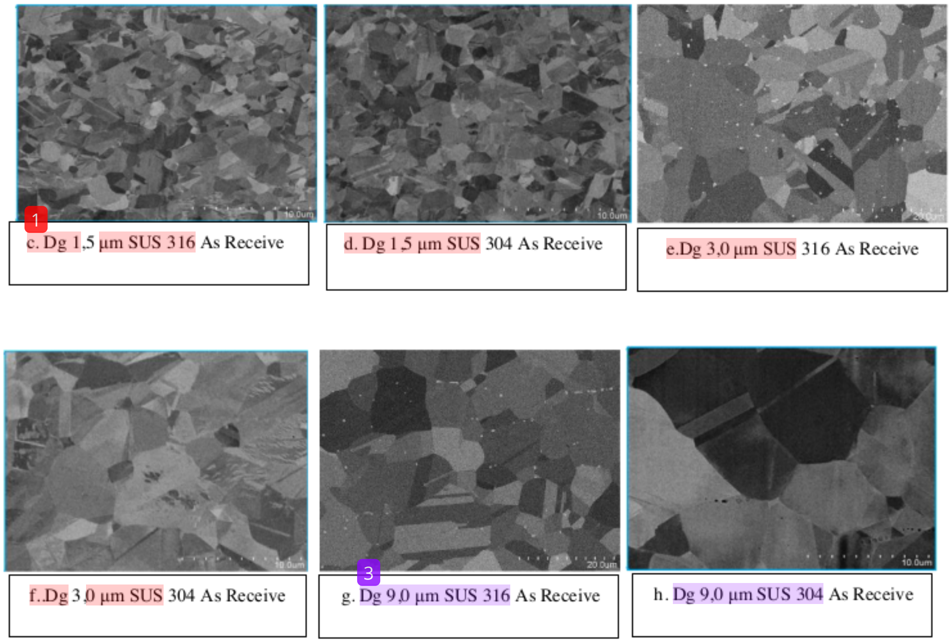
Table.1. Chemical composition thin metal foils of SUS 304

	C	Si	Mn	P	S	Ni	Cr
Min						8,00	18,00
Max	0,08	1,00	2,00	0,045	0,030	10,50	20,00
	0,05	0,39	1,10	0,030	0,004	8,03	18,01

Table.2. Chemical composition thin metal foils of SUS 316

	C	Si	Mn	P	S	Ni	Cr	Mo
Min						12.00	16.00	2.00
Max	0.030	1.00	2.00	0.045	0.030	15.00	18.00	3.00
	0.012	0.66	1.20	0.035	0.001	12.22	17.41	2.07

From the chemical composition, the quantity of carbon in SUS 304 is higher than SUS 316. It means that the quantity of martensite phase in SUS 304 will higher than SUS 316 because of plastic deformation. Martensitic phase and carbide compound may formed in grain matrix that will increase the strength of thin foils. Because of plastic deformation or heating and quenching affect to martensitic phase transformation (MPT). Plastic deformation promote to dislocation motion. Dislocation motion in slip band of lattice crystal will change the crystal structure from FCC (face centre cubic) toward BCT (body centre tetragonal). The quantity of nickel in SUS 316 almost 4-5% higher than SUS 304 thin metal foils. This indicated that the ductility and toughness of SUS 316 is higher than SUS 304, because nickel is austenitic former element that has high strength and ductility. But, the quantity of chromium element as ferrite former in SUS 304 is higher than SUS 316 thin metal foils. This means the chromium carbide easier to be formed in grain matrix or boundary and also increase the strength of thin metal foils when plastic deformation applied to thin metal foils. The higher nickel elements in stainless steel the more difficult of martensitic transformation or the more difficult of austenite transform to become martensite, because nickel is austenitic stabilizer. It needs higher energy to change the austenitic phase transform to become martensite.


c. Dg 1,5 µm SUS 316 As Receive

d. Dg 1,5 µm SUS 304 As Receive

e.Dg 3,0 µm SUS 316 As Receive

f..Dg 3,0 µm SUS 304 As Receive

g. Dg 9,0 µm SUS 316 As Receive

h. Dg 9,0 µm SUS 304 As Receive

Fig.1. SUS 304 & 316 thin metal foils with different grain size (Dg) as receive

From fig 1, showed typical microstructure of various Dg, since fine grain until coarse grain. According to hall-petch equation, it is well known that grain size affect to mechanical properties of materials. Materials which have fine grain will have higher tensile and yield strength than materials which have coarse grain. The surface roughness in thin metal foils of SUS 304 and SUS 316 will different, because of the same tensile stress state subjected to thin metal foils with various Dg.

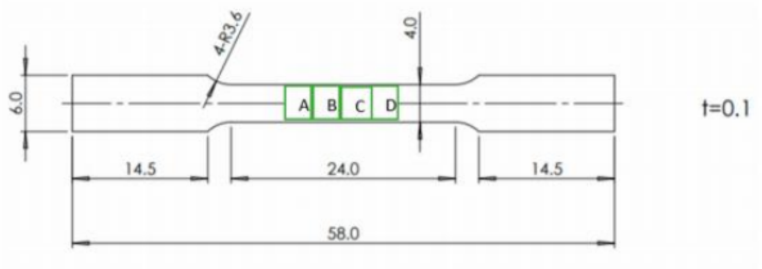


Fig.2. Specimen of Tensile Test

Based on fig.2. Thin metal foils of commercial SUS 304 and 316 with width 4,0 mm, thickness 0,1mm and gauge length 20 mm using standard of DIN 50125. The sample made in dog bone type as shown in the figure.2.

2.2. Methode

The samples annealed in 400°C for one hour to release residual stress and increase activity of slip band movement. Before sample subjected with uniaxial tensile stress state, cleaned using ethanol combined with ultrasonic vibration for 30 minutes to increase the cleaning of surface. Sample tensiled until five steps with constant strain. After sample subjected with uniaxial tensile stress state, surface roughness measured using confocal laser microscope using Keyence Confocal Laser Microscope (VE 8800, Keyence Co). Tensile test using a commercial tensile test machine of Autograph AG-IS 50 KN produced by Shimadzu Corporation with capacity 50 KN.

Surface roughening behavior of stainless steel 304 and 316 with various grain size investigated using uniaxial tensile test. Uniaxial tensile test was conducted step by step using constant strain over the yield point of thin metal foils. The gauge length of thin metal foil is 20 mm. Width of thin foil is 4 mm and 0,1 mm thickness. The used of fillet radius is 3,6 mm. In order for consistency, The uniaxial tensile test machine using a commercial tensile test machine of Autograph AG-IS 50 KN (Shimadzu Corporation). The strain rate of uniaxial tensile test is 1,6 x 10^{-3} m s^{-1}. The surface roughness behavior were measured and observed for different grain size, different materials and constant thickness. The elongation was measured optically with video noncontact extensiometer (DVE-201, Shimadzu Corp), because of contact extensiometer could not be pasted onto the metal foil. Surface roughness during deformation was measured using uniaxial tensile testing machine that halted for every step. In universal tensile testing machine, the sample subjected using uniaxial tensile stress state for each step, the tensile test was halted then the specimen was taken out from the chuck for measuring surface roughness behavior using Keyence Confocal Laser Microscope (VE 8800, Keyence Co). The area of surface roughness measurement is in the centre point of A,B,C, and D in the rolling direction at each step using contact surface roughness measurement. The surface roughness measured until five step in the same position with constant strain. beside surface roughness, the Rz value was evaluated. The area of surface roughness measurement in the length of 0,7 mm.

3. Experimental results

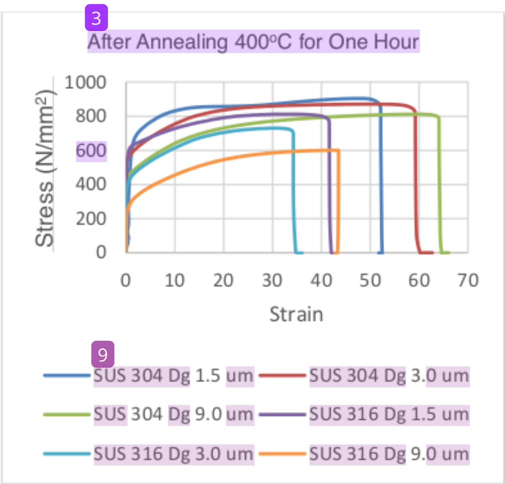


Fig.3. Deformation behavior of thin metal foils

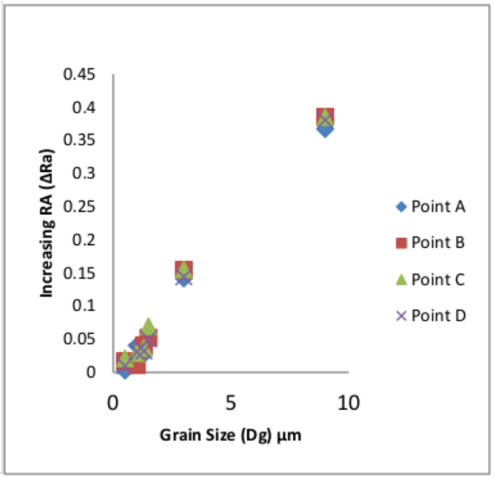


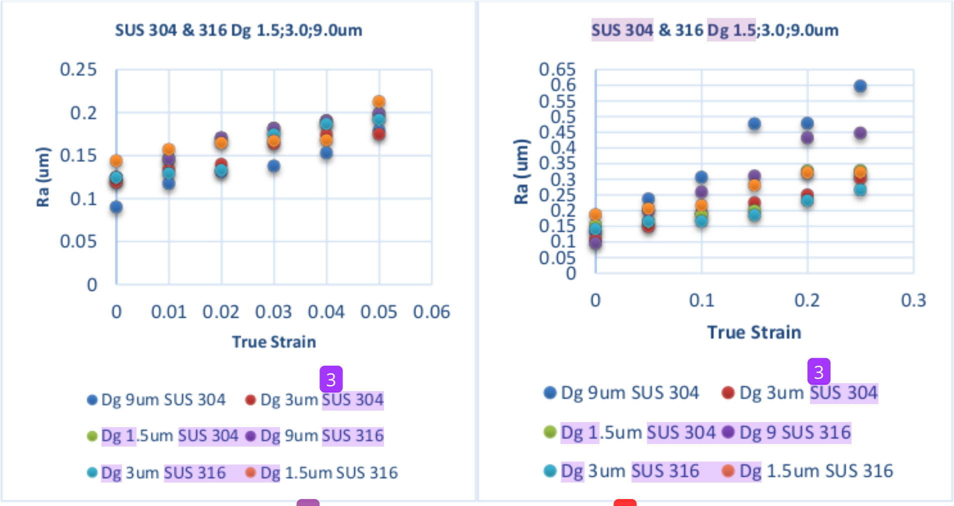
Fig.4. Increasing Ra with 5,0 % strain

Fig.3. is true stress – strain curve of thin metal foils SUS 304 and SUS 316 with various Dg. Fracture strain increases with increasing grain size. In contrast, tensile strength decreases with increasing grain size from thin metal foils SUS 304. For thin metal foils SUS 316 fine grain, low fracture strain and low tensile strength were also obtained. Various fracture strain and tensile strength behavior of thin metal foils may affect to surface roughness behavior of SUS 304 thin metal foils.

Samples were subjected with uniaxial tensile stress state step by step until five steps with the number of one-time strain level is 5,0%. Then after the sample subjected with uniaxial tensile stress state until five stages, the amount of surface roughness increase is calculated at points A, B, C and D. The results of the total increase in the value of surface roughness after undergoing tensile testing for five stages on thin metal foils are shown in Fig. 4.

Fig.4. is the correlation between increasing surface roughness with various Dg. As Dg increases, surface roughness increases. surface roughness increases higher for coarse grain. while for fine grains, an increase in surface roughness is low. The increase in surface roughness goes hand in hand with an increase in fracture strain but inversely proportional to the increase in SUS 304 thin metal foils strength. SUS 316 thin metal foil fine grain fracture strength is low and the increase in surface roughness is also low. Both on SUS 304 and SUS 316 fine grain have the same tendency in fracture strain and increased surface roughness.

Factor affect to the yield stress of the grains is their orientation with respect to the loading direction. Thus beside Dg, surface roughening and the inhomogeneous yield behavior depend also on the grains orientation distribution (33). According to fig.3. thin foil materials have higher ductility for coarse grain indicated with higher fracture strain compared to fine grain indicated with lower fracture strain. Furthermore, for fine grain in SUS 304, the strength and yield point is higher compared to coarse grain and have good agreement with hall–petch equation. Fracture strain and tensile strength behavior may affect to surface roughening behavior with various Dg. Based on fig. 4, the surface roughness increases higher for the coarse grain of SUS 304 compared to fine grain of SUS 304 and SUS 316 thin foils. Because, the ductility and grain share for the coarse Dg is higher than the fine Dg. Furthermore, when the grain is larger, the share of surface grain is increased, which result in the decreasing flow stress as well as lower ductility (36) . In the consequence, the dislocation density, flow stress is lower for coarse Dg than fine Dg (31). The increased surface roughness in whole area of investigation in fine and coarse grain such as in point A,B,C and D are nearly the same. It means the surface roughness behaviors are the same in whole area of gage length, because of the same fracture strain in point A,B,C and D.



A. 1,0 %true strain B. 5,0%true strain

Fig.5. Surface roughening (Ra) behavior of thin metal foils SUS 304 & SUS 316

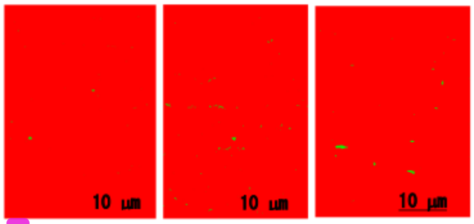
Low strain is a 1,0% strain applied to thin metal samples. High strain is a strain of 5,0% that is applied on thin metal samples. Each sample was subjected by tensile stress with a low strain of five stages. Surface roughness is investigated at each stage of tensile testing. Thus, five strain values and five surface roughness values are obtained. Then, each sample was also subjected with tensile stress state at a high strain of five stages. The sample is investigated for its surface roughness value at each stage of tensile testing in order to obtain five surface roughness values and five strain values. Then, a surface roughness curve for low strain is obtained as shown in figure 5 part A and a surface roughness curve for high strain obtained as shown in figure 5 part B.

ASS (SUS 304 & SUS 316) thin metal foils subjected with uniaxial tensile test using low strain at 1,0% as shown in figure 5 section A and high strain at 5,0 % as shown in figure 5 section B. The results show that surface roughness increases proportionally for coarse grains and for fine grains. Samples were subjected with uniaxial tensile stress using two kind of strain at 1,0 % for low strain and at 5,0% for high strain, then taken out of the tensile testing machine and measured its surface roughness. This test is repeated up to five stages. The results of tensile testing and observation of surface roughness behavior step by step until five stages with a low strain of 1,0 % are shown in Figure 5 section A. The results in the observation of the tensile test and the behavior of the ASS thin metal foils surface roughness step by step until five stages with a high strain of 5,0% are shown in Figure 5 section B.

The surface roughness (Ra) increase with the increasing plastic strain both in 1,0% and 5,0% strain level (fig. 5).The Dg 0,5µm only measured at 1,0% strain, because the sample fracture at one time of tensile test at 1,0% strain level. Surface roughening increase proportionally lower for fine grain compared to coarse grain both in 1,0% and 5,0% strain because lower ductility and lower increasing surface roughness for fine grain compared to coarse grain. The lower ductility in thin metal foils occur in fine grain which indicated by higher work hardening after uniaxial tensile stress state. The harder the grain the more difficult of surface roughening occurred. Low ductility and low increased surface roughness in fine grain of SUS 316 is quite similiar with fine grain of SUS 304, thus the grain strength of SUS 316 is nearly the same with SUS 304. The surface roughening increase proportionally higher in coarse grain than fine grain both in 1,0% and 5,0% strain level, because of higher ductility and higher increased roughness. the higher ductility and higher increasing surface roughness indicate the weaker of a grain in coarse grain compared to fine grain of thin metal foils. In consequence, coarse grain more easier to deform than fine grain, thus surface roughness in coarse grain is higher compared to fine grain. Furthermore, according to the surface layer theory, with the increase of Dg while keeping the foil thickness constant, the share of surface grain increases, which result in the decreasing of flow stress (36).Surface roughening is closely related to the mutual rotation of grains. Different deformation behavior of individual grain affect in increasing surface roughness of thin metal foils (30).

The increase of surface roughness (ΔDg) in Dg 1,5µm of SUS 304 to SUS 316 thin metal foils is 0,005µm in low strain . ΔDg in Dg 9,0µm is 0,015µm in low strain level. ΔDg in high strain level in Dg 1,5µm is 0,06µm and ΔDg in high strain level in Dg 9,0µm is 0,114 µm.

4. Discussion

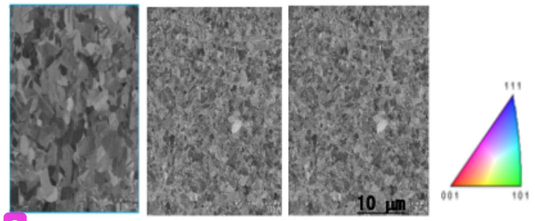


Dg 1,5µm.As Receive

Dg 1,5µm.5,0% Strain

Dg 1,5µm.25% Strain

A.1. EBSD phase mapping in Dg 1,5µm SUS 316

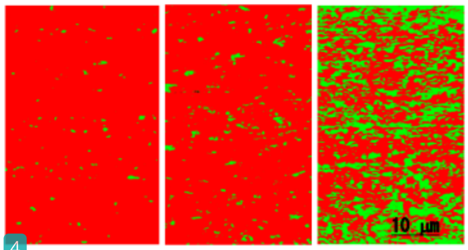


Dg 1,5µm.As Receive

Dg 1,5µm.5,0% Strain

Dg 1,5µm.25% Strain

B.1. EBSD IPF mapping in Dg 1,5µm SUS 316

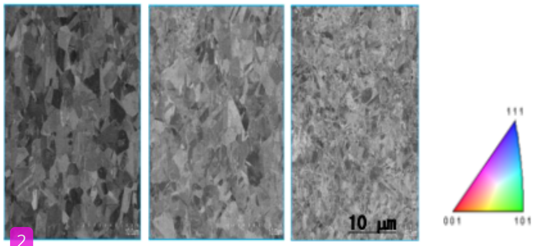


Dg 1,5µm. As Receive

Dg 1,5µm. At 5,0% Strain

Dg 1,5µm.25% Strain

A2. EBSD phase mapping in DG 1,5µm SUS 304

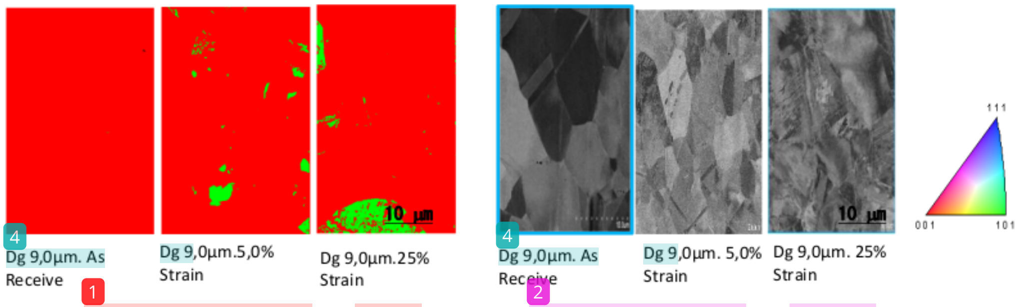


Dg 1,5µm. As Receive

Dg 1,5µm.5,0% Strain

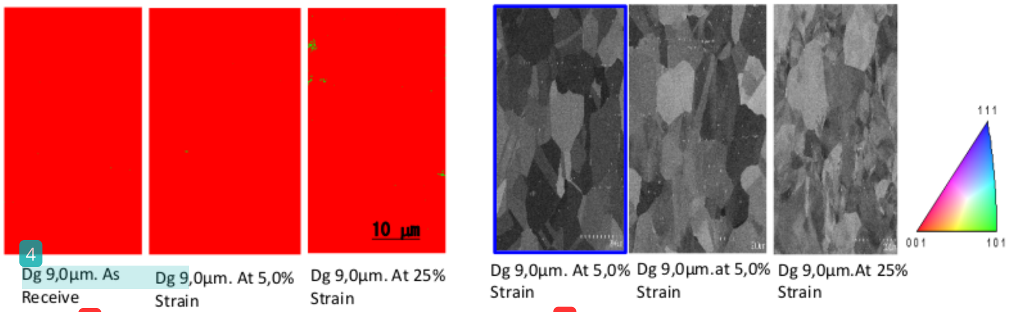
Dg 1,5µm.25% Strain

B2. EBSD IPF mapping in DG 1,5µm SUS 304



A3. EBSD phase mapping in DG 9,0µm SUS 304 & SUS 316

B3. EBSD IPF mapping in DG 9,0µm SUS 304 & SUS 316



A4. EBSD phase mapping in DG 9,0µm SUS 304 & SUS 316

B4. EBSD IPF mapping in DG 9,0µm SUS 304 & SUS 316

Fig.7. SEM-EBSD mapping for SUS 304 & SUS 316 thin metal foils

The result of SEM-EBSD experiment as shown in fig.7. Section A.1.is EBSD result of SUS 316 fine grain. The red color is gamma (γ) iron known as FCC metastable ASS and the green color is alpha (α) iron known as MPT. No MPT occur in SUS 316 both in low and high strain, because there are not change color from red to green in SUS 316 as shown in the fig.7.section A.1. Grain deformation occur in fine grain of SUS 316 thin metal foils because there are grain change since as receive, low (1,0%) strain and high (5,0%) strain as shown in fig.7. section B.1. From the SEM result, the grain deformation at high strain level is larger than low strain level as shown by grain change morphology since low strain until high strain. There are not MPT occurred both in low (1,0%) strain level and high (5,0%) strain level, because the SUS 316 thin metal foil consists of more nickel as austenitic stabilizer compared to SUS 304 thin metal foil. It is difficult to transform austenitic phase in SUS 316 to become MPT even in high strain level because of high austenitic stabilizer such as nickel. The surface roughening in fine grain for SUS 316 and SUS 304 almost the same both in low and high strain level, because the grain strength affected by very high MPT, local grain misorientation in SUS 304 and high local grain misorientation in SUS 316. Plastic deformation that occurs in hard fine grain of SUS 316 thin metals and very hard fine grain of SUS 304 thin metals occur in intergrain. Intergrain deformation not much affect in increasing surface roughness.

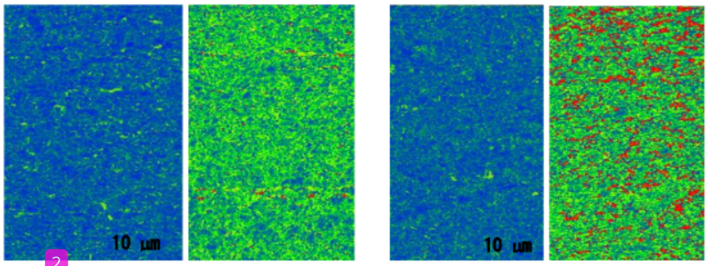
Based on SEM-EBSD result as shown in fig.7. section A.2. is EBSD result of SUS 304 fine grain. The results show that MPT transformation mechanism in as receive condition, low and high strain thin metal foils. The MPT and Mf is very high indicated by very high color change since red as austenitic phase to become green as MPT at high strain level. Grain deformation occur in SUS 304 thin metal foils indicated by grain change since low strain until high strain. Based on SEM result as shown in fig.7. section B.2. that the grain deformation at high strain is larger than low strain indicated by grain change morphology.

MPT occur higher in higher strain level compared to low strain level in SUS 304 coarse grain as shown in fig.7. section A3. Grain deformation in coarse grain of SUS 304 is larger than fine grain and more severe grain deformation occur as shown in fig.7. section B.3, compared to fine grain. That`s the reason of the higher increasing surface roughness in coarse grain compared to fine grain. Furthermore, the surface roughness increase higher proportional with the same strain level in coarse grain compared to fine grain during uniaxial tensile stress state. Based on EBSD result, the MPT in coarse grain is lower than fine grain, thus the grain strength become lower, the inhomogeneous grain become higher compared to fine grain and surface roughness become higher because coarse grain become easier to deform.

MPT does not occur in coarse grain of SUS 316 thin metal foil after plastic deformation both in low and high strain level as shown in fig.7 section A4. Because in SUS 316 thin metal foil, the austenitic phase is more stable than SUS 304 thin metal foil. The grain deformation occur more severe in coarse grain of SUS 316 thin foil at high strain level compared to low strain level as shown in fig.7 section B4. It means the grain deformation is larger at high strain level and the Ra increase higher in strain level compared to low strain level in SUS 316 thin metal foils.

MPT in fine grain is higher than coarse grain of SUS 304 thin metal foils. Because, in fine grain, the slip band intersection is higher than coarse grain with the same plastic deformation. Slip band intersection is the place of martensitic embryo and nucleation. The more slip band intersection, the higher MPT in a grain. In the fine grain the probability of slip band intersection is higher compared with coarse grain with the same strain level.The higher MPT in a grain affect to higher strength of a grain that indicated by lower surface roughening value with the same strain level. Both in fine grain and coarse grain have the obvious grain deformation with the same strain level. There are larger grains deformation in coarse grain compared to fine grain that indicated in coarse grain has a weaker strength compared to fine grain (25).

When the strain increase, the hardening surface increase. The martensitic volume fraction increase with increasing plastic deformation (16). This conclusion is intersected with my result that with the increasing strain, the slip band intersection increase and the volume fraction of martensite increase. The increase Mf and MPT affect in hardening surface of grain that cause lower Ra or Rz value for the fine grain. With the increasing strain, the adiabatic heating increase in the grain that lead to MPT. Adiabatic heating activate movement of slip band and intersection each other that promote martensitic nucleation. Furthermore, when the grain is larger, the share of surface grain is increase, which result in the decreasing flow stress (37). Lower dislocation density affect to weaker grain indicated by lower flow stress that correlate to lower MPT after tensile test step by step until five times both in fine and coarse grain. Based on Olson Cohen (OC) model and theory, the slip band intersection become martensitic embryo and nucleation. Thus, the more intersection, the higher embryo and nucleation, hence the higher martensitic volume fraction in a grain. The OC model defines the transformation curve only as function of plastic strain or environmental temperature. Olson and cohen (OC) equation only for austenitic that will transform to martensite after plastic deformation (36). Thin foil materials SUS 304 with the same thickness will have a decrease number of grains as the size of the grains increases. When the grain size increase in the same area, thus the grain obstacle decrease and the grain easier change its orientation because of plastic deformation. In consequence, the surface roughening increase because of plastic deformation with the same strain level. The OC model is in good agreement with the current research as using function of plastic strain. Strain induced martensitic transformation (SIMT) occurred in a sequential manner of austenite → ε martensite occur at low strain → α` martensite occur at high strain with increasing strain in austenite (17).



Dg 1,5µm. SUS316 As receive

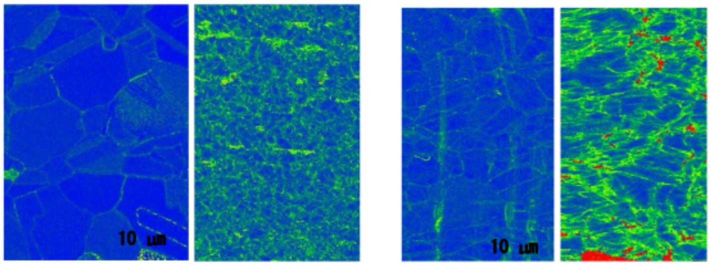
Dg 1,5µm SUS316. 25,0% Strain

A1. EBSD KAM in DG 1,3µm SUS 316

Dg 1,5µmSUS 304 As receive

Dg 1,5µm SUS304 25,0% strain

A2. EBSD KAM in DG 1,5µm SUS 304



Dg 9,0µm SUS 316 As Receive

Dg 9,0µm SUS316 25,0% Strain

A3.EBSD KAM in DG 9,0 µm SUS 316

Dg 9,0µm SUS304 As Receive

Dg 9,0µm SUS304 25,0% Strain

A4.EBSD KAM in DG 9,0 µm SUS 304

🔴 = 5° grain misorientation

🟢 = 2° grain misorientation

Fig.8. KAM mapping for SUS 304 & SUS 316 thin metal foils

Kernel average misorientation (KAM) obtained from the calculation of the misorientation between the center point and all the surrounding points in the kernel are calculated and averaged which show the local misorientation value of the center point. From KAM calculation obtained two degrees grain misorientation indicated in blue color and obtained five degrees grain misorientation indicated in red color. Grain that consist of blue color has high strength mechanical property and a grain that consist of red color has very high strength grain property. Based on fig.8 section A1, the grain misorientation is high indicated by the fully two degree grain misorientation. It`s indicated that the the grain strength in SUS 316 thin metal foils is high. The grain misorientation is highest in SUS 304 fine grain thin metal foil as shown in fig.8 section A2 that have very high grain misorientation indicated by fully two degree grain misorientation and five degree grain misoreintation. The red color volume in fine grain SUS 304 thin metal foils (fig.8. section A2) is higher then red color volume in fine grain SUS 316 (fig.8. section A1) and coarse grain SUS 304 (fig.8. section A3) thin metal foils. The green color in fine grain SUS 304 thin metal foils equal to green color fine grain SUS 316 thin metal foils. The green color in coarse grain SUS 304 thin metal foils is lower than another materials. It means that the grain strength in fine grain SUS 304 thin metal foils is highest than all materials.

Based on fig. 8 section A4, the red color is five degree (5°) and green color is two degree (2°), indicate that the red color has higher misorientation then green color. The local misorientation in fine grain both in SUS 304 and 316 are different as shown in fig.8. The degree of grain misorientation represented by red color is higher than green color, it means that SUS 304 with fine grain has higher misorientation than SUS 316 with fine grain. As shown by EBSD in fig 8, the number of red misorientations on SUS 304 thin metal foils is more than the misorientation of red on SUS 316 thin metal foils. It means that a grain of SUS 304 is harder than the grain of SUS 316. Grain deformation mechanism for ASS fine grain both in SUS 304 and SUS 316 thin metal foils are intergrain deformation (30,33). Intergrain deformation almost does not change the surface roughness of thin metals with fine grain. So that the surface roughness in SUS 304 thin metal foils fine grain is almost the same compared to SUS 316 thin metal foils fine grain, even though grain of SUS 304 is harder than a grain of SUS 316.

Uniaxial tension with the same strain applied to thin metal foils affect on increasing the average roughness. Onset of diffuse necking occurred when the rate of increases of the average roughness become large. The relative inclination between neighboring grain in the direction normal to the surface implies the roughening of the free surface. Individual grain as well as the mountain and valley of the roughened surface elongates in the loading direction during uniaxial tension. In the same area, the difference of grain deformation in low population increases higher compared to high population of grain with the same strain level. When the strain applied, the standard deviation and the average value of the inclination angle of grain in direction normal to the surface gradually increase. This is the primary cause of the increase in surface roughness to be considered. Inhomogeneous deformation inside grain increases with the applied strain showed by the average roughness of grain (30). When the inclination is large, the surface roughness become high. In fine grain thin metal foils the relative inclination between neighboring grain is low, thus the surface roughness become low, even in the large strain. in the fine grain SUS 304 and SUS 316 thin metal foils, the difference of grain deformation is low affect to the relative inclination between neighboring grain in the direction normal to the surface is low, thus the surface roughness increases low. This is the reason why the surface roughness in fine grain SUS 304 and SUS 316 thin metal foils approaches the same. The local misorientation in fine grain higher than coarse grain. The higher local misorientation affect to higher strength in a grain, because the dislocation density increased and dislocation movement become more difficult. Thus in the fine grain more difficult to deform compared to coarse grain with the same strain level. In consequence, the surface roughness in fine grains are lower than coarse grain.

5. Conclusion

1. MPT only occur in SUS 304 thin metal foils both in fine or coarse grain because of high chromium element as ferrite stabilizer and carbon element as martensite element. As ferrite stabilizer, chromium accelerate MPT formation. Beside that, chromium could become carbide compound that increase the strength of a grain.
2. MPT not occur in SUS 316, because of high nickel element as austenite stabilizer. It is very difficult to transform austenite to become MPT with the same strain level. local misorientation in SUS 316 thin metal foils is high. It indicates the mechanical property of a grain is hard. local misorientation on thin metal foils SUS 304 is very high. It indicates the mechanical property of grain in SUS 304 thin metal foils is very hard.
3. Ra increase proportional in low and high strain level on SUS 304 and SUS 316 thin metal foils both in coarse grain and fine grain. Surface roughness increase higher for SUS 304 compared to SUS 316 thin metal foils with coarse grain, because SUS 304 coarse grain is more inhomogeneous than SUS 316 coarse grain thin foil.
4. Inhomogeneous grain characteristic affected by MPT is higher than GMO shown by higher Ra in coarse grain SUS 304 thin foil with the same strain level compared to coarse grain of SUS 316 thin foil.
5. In fine grain, local grain misorientation in SUS 304 thin metal foils is higher than SUS 316 thin metal foils, indicated by higher quantity of red color in SUS 304 grain compared to SUS 316 thin metal foils.

6. Ra behavior in fine grains of SUS 304 are higher than SUS 316 thin metal foil because of the inhomogeneous grain in SUS 304 thin foil is higher than SUS 316 thin metal foil. Grains inclination affected by fine grain deformations are not the same both in SUS 316 and SUS 304 thin metal foils after annealing.
7. MPT may be the most important factor that enhance the surface roughening in thin metal foils of stainless steel after plastic deformation.

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