Constitutive Model of The Surface Roughening Behavior of Austenitic Stainless Steel

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Constitutive Model of The Surface Roughening Behavior of Austenitic Stainless Steel

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Abstract.

Austenitic stainless steel such as SUS 304 and SUS 316 have wide application in kind field of industry. Uniaxial tensile test until five step and observe surface roughening behavior in room and elevated temperature was used to reveal the surface roughening behavior both in room and elevated temperature. The surface roughening behavior in room temperature was different compared to elevated temperature. SUS 304 increase higher than SUS 316 in coarse grain, but in fine grain increase similiar at the same strain level in room temperature. SUS 304 and SUS 316 increase similar both in coarse grain and fine grain at elevated temperature. Based on SEM-EBSD result that surface roughening depend on the inhomogeneous and homogeneous grain strength that indicated by the martensitic phase transformation (MPT) dispersion in a grain after uniaxial tensile test. When MPT spread uniform affect to homogeneous grain strength. When MPT spread not uniform affect to inhomogeneous grain strength that show the surface roughening increase higher compared to homogeneous grain strength. The effect of MPT was higher than grain misorientation in showing inhomogeneous grain strength.

Keywords : inhomogeneous grain strength; homogeneous grain strength; room temperature; elevated temperature; surface roughening.

1. Introduction

In this decade, the demand of micro part increase unabated. Stainless steel such as SUS 304 and SUS 316 have wide application in micro manufacturing industry.

2. Materials and methode.

2.1. Materials

In this research, author use SUS 304 and SUS 316 thin metal foils of SUS 304 and SUS 316. The material condition for room and elevated temperature was similar with previous result such as sample dimension, as receive microstructure, how to calculate grain size and chemical composition (Aziz., 2021). In room temperature, author use two kind of materials such as SUS 304 and SUS 316. The thickness was 0.1 mm, the grain size (Dg) was 1.5μm; 3.0 μm and 9.0 μm both in SUS 304 and SUS 316 thin metal foils.

2.2. Methode

The methodology in room temperature has been explained in previous research (Aziz.,2021). The methodology in general such as using uniaxial tensile stress state until five steps and surface roughness was measured for every step. After surface roughness measured until five steps, phase transformation and grain misorientation was observed using SEM-EBSD methode.

The methodology on surface roughening behavior investigation at elevated temperature using resistance heating method. The proportional (P), integral (I) and derivative (D) were obtained. The value of P = 113.6; I = 1.5; D = 0.2. The resistance heating was conducted at 500°C for three minutes for every step of tensile test. The emissivity of the sample was 0.94. The thermo sensor camera used in this experiment was Optris Xi-400, made in Japan. The uniaxial tensile test using The AGX-50KNVD machine, with loading capacity until 50 KN. The uniaxial tensile test machine produced by Shimadzu, Japan. The surface roughening behavior was investigated using OLS - 5000 laser microscope, produced by Olympus Co., Japan.

3. Result and Discussion

The hardness of martensitic phase transformation was higher than grain misorientation in the same strain level.

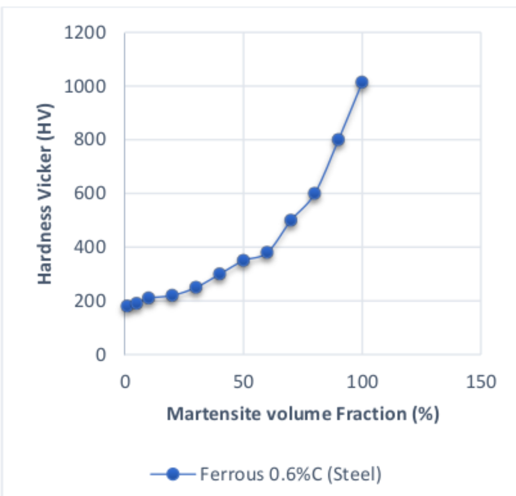
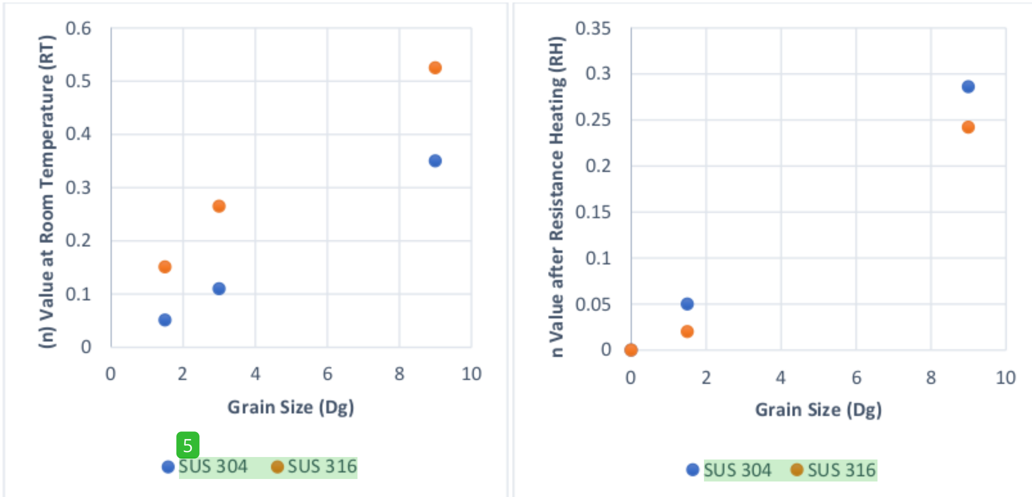


Figure 1 (J.Mola et al.,2018) Relationship between MPT and hardness in Steel 0.6%C

Based on figure 1, the hardness of material increase with increasing martensitic phase volume fraction (Mf). The hardness increase hyperbolic with the increasing Mf. The hardness increase very high when the MF over than 50 %. The increasing of Mf affect to the increasing grain strength that will affect to the increase of whole material. Based on figure 1, means that the grain which contain the martensitic phase transformation (MPT) will have very high strength than the grain without MPT. When the MPT spread inhomogeneous in grain, the inhomogeneous grain strength will become very high.



A.Room Temperature

B. High Temperature

Figure. 2 Work hardening Versus Grain size

Based on figure 2A, the work hardening for SUS 316 is higher than SUS 304 for every grain size (Dg) in room temperature. it means that SUS 316 TMF has more uniform of deformation distribution in the work piece. When the uniform deformation distribution in the workpiece occur, the grain become more homogeneous. The homogeneous grain deformation affect to lower increasing surface roughness compared to inhomogeneous grain deformation with the same strain level. Thus, in room temperature, SUS 304 TMF showed higher surface roughness than SUS 316 TMF with the same strain level.

Based on figure 2B, at elevated temperature, the work hardening of SUS 304 was higher than SUS 316 TMF. It means the SUS 304 TMF grain deformation distribution in the work piece become more uniform or more homogeneous (Zheng et al.,2014). Since the SUS 304 TMF has more homogeneous than SUS 316, the increase of surface roughness in SUS 316 will become higher than SUS 304 TMF with the same strain level. The phenomena between room and high temperature were different in showing work hardening (n) value.

Based on figure 2A and figure 2B, with the increasing grain size, the work hardening increased. It means, the grain deformation distribution between fine grain and coarse grain were different. The difference of work hardening distribution affect to difference of surface roughness value between fine grain and coarse grain with the same strain level. In coarse grain, the grain deformation more inhomogeneous than in fine grain at room and at elevated temperature.

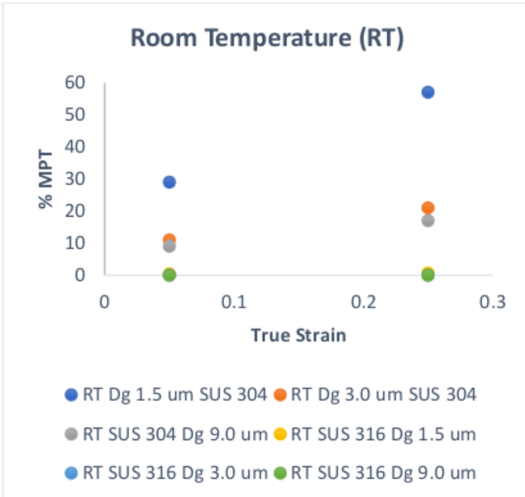


Fig.3. MPT behavior in room temperature

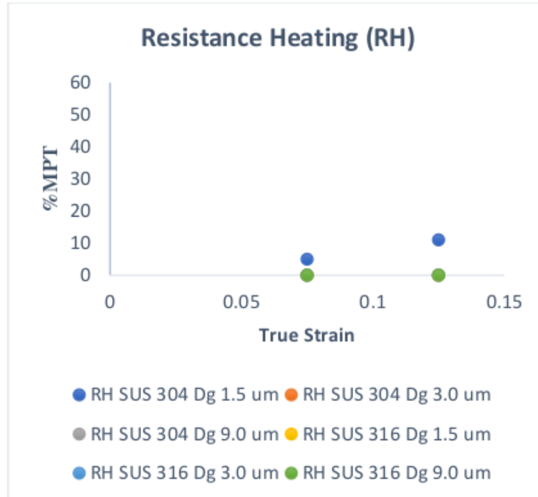


Fig.4. The resistance heating behavior.

Fig. 3 explain about the martensitic phase transformation (MPT) behavior in room temperature and Fig.4 explain about the resistance heating behavior.

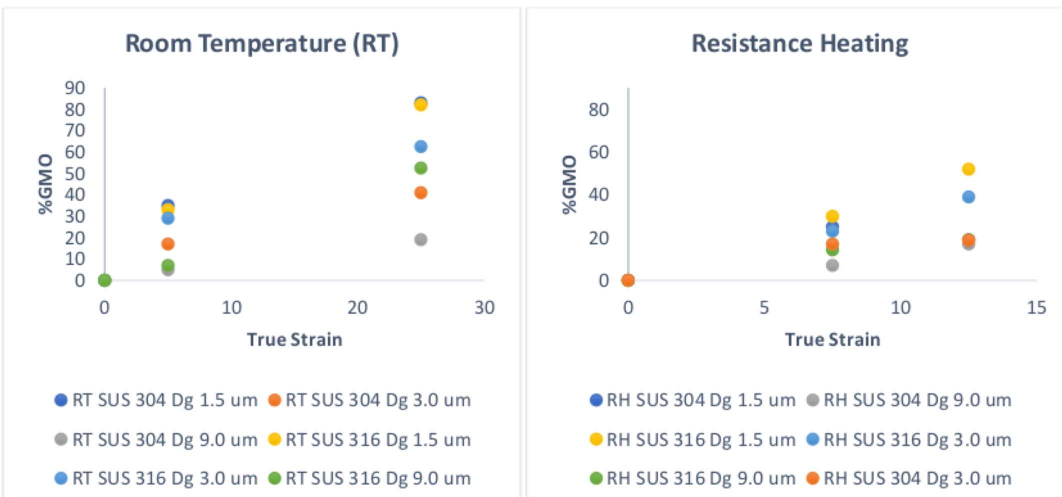


Fig.5

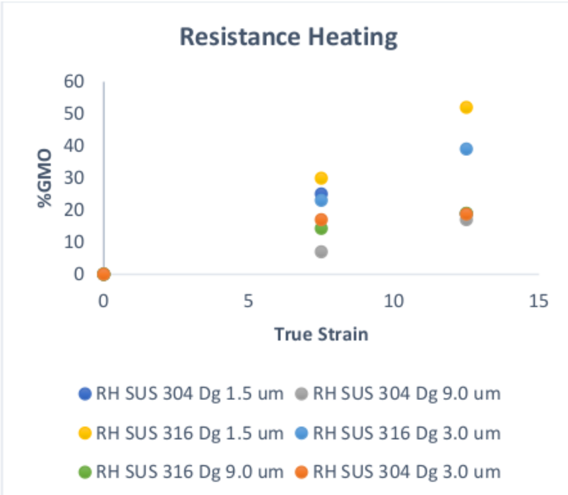


Fig.6

According to figure 3, there are no MPT in SUS 316 TMF, and MPT spread homogeneous in fine grain both in low and high strain level of SUS 304 TMF. MPT spread inhomogenous in coarse grain of SUS 304 TMF and the quantity of MPT in coarse grain of SUS 304 TMF much lower than fine grain. Since MPT spread inhomoigeneous in coarse grain, the surface roughness in coarse grain of SUS 304 TMF become the highest than SUS 304 fine grain, SUS 316 TMF coarse and fine grain with the same strain level.

According to figure 4, the MPT decrease much in fine grain of SUS 304 TMF because of resistance heating during tensile test. The MPT become disappear in coarse grain of SUS 304 TMF and make the grain strength become more homogeneous than at room temperature. since the MPT disappear in coarse grain of SUS 304 TMF at elevated temperature, the surface roughness in SUS 316 become higher than the surface roughness of SUS 304 TMF (Aziz et al.,2021).

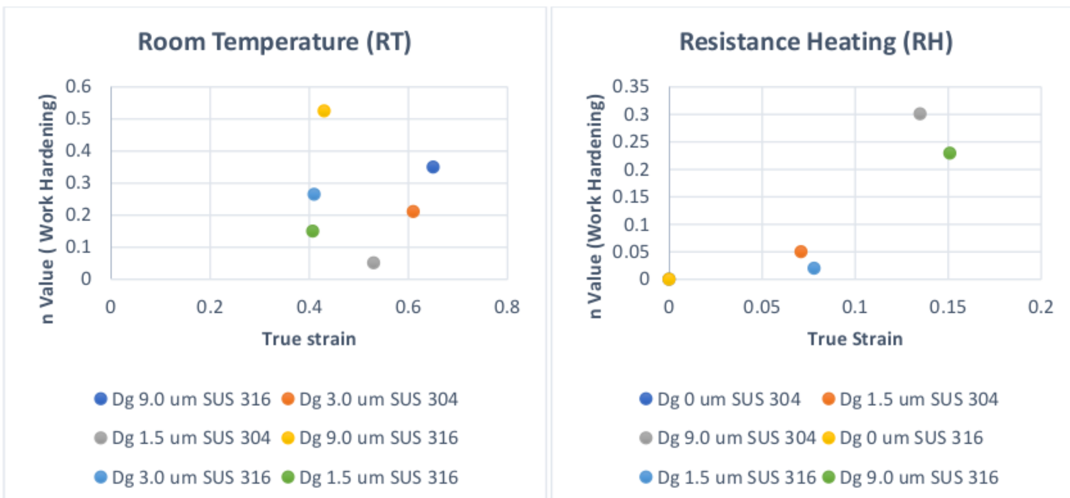
According figure 3 and figure 4, MPT increase with increasing strain level both in room and at elevated temperature. Because, with increasing strain level, the slip band intersection as the place of martensitic embryo and nucleation become increase (Tomita et al.,).

Narutani et all (4) concluded that, the dislocation density increase with increasing tensile strain level. The increasing of dislocation density is in a good agreement with the increasing MPT after tensile test step by step. The MPT comes from slip band intersection, which affect on increasing the dislocation density in the materials (Tomita et al.,).

According to figure 5, the GMO decrease with increasing grain size (Dg). The GMO increase higher in SUS 304 in comparison to the SUS 316 TMF both in fine and coarse grain. The GMO spread inhomogeneous for coarse grain and spread homogeneous for fine grain. The GMO spread homogeneous for fine grain with similar manner between SUS 304 and SUS 316 TMF. The GMO spread more inhomogeneous for coarse grain of SUS 316 than SUS 304 TMF, but, the surface roughness behavior in SUS 304 coarse grain was higher than SUS 316 TMF coarse grain. In SUS 316 TMF, there are no MPT occur with the same strain level compared to SUS 304 TMF. The higher surface roughness in SUS 304 affected by the MPT that spread inhomogeneous in the grain at room temperature. Thus, the effect of MPT was much higher than GMO.

According to fig 6, at elevated temperature (E.T.), the GMO increase higher for fine grain compared to coarse grain in the same strain level. The surface roughness of SUS 316 increase higher than SUS 304 TMF. The MPT disappear in SUS 304 coarse grain, the MPT decrease much for fine grain. The GMO become one factor that affect on surface roughness behavior in coarse grain. According to the GMO behavior, the SUS 316 more inhomogeneous than SUS 304 TMF coarse grain and the surface roughness in SUS 316 TMF coarse grain increased higher than SUS 304 coarse grain TMF.

The grain misorientation (GMO) in room temperature both in SUS 304 and SUS 316 TMF higher than at elevated temperature. The quantity of GMO decrease because of resistance heating both in SUS 304 and SUS 316 TMF. Based on previous result (Aziz et al., 2021), because of resistance heating, the MPT disappear in coarse grain of SUS 304 TMF, the surface roughness only affected by the GMO. According to fig.6, the GMO in coarse grain of SUS 304 TMF decrease in high temperature compared to room temperature. The GMO in SUS 316 TMF was higher than SUS 304 TMF at elevated temperature. The inhomogeneous grain strength in SUS 316 TMF was higher than SUS 304 at elevated temperature, thus the surface roughness in SUS 316 TMF was higher than SUS 304 TMF (Aziz et al.,2021).

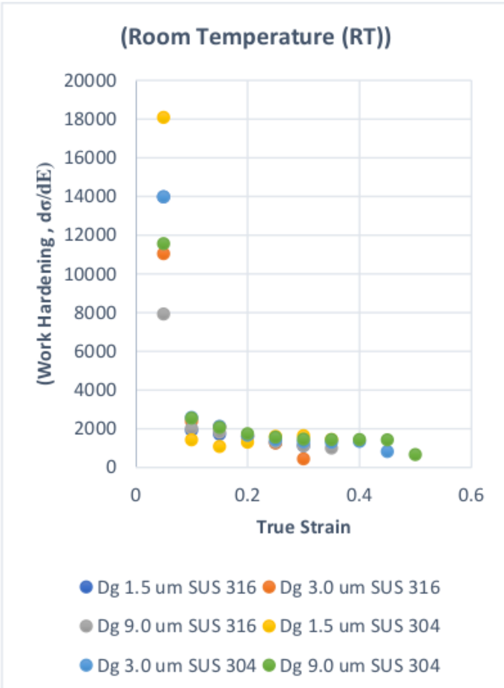


A. Room Temperature B. High Temperature

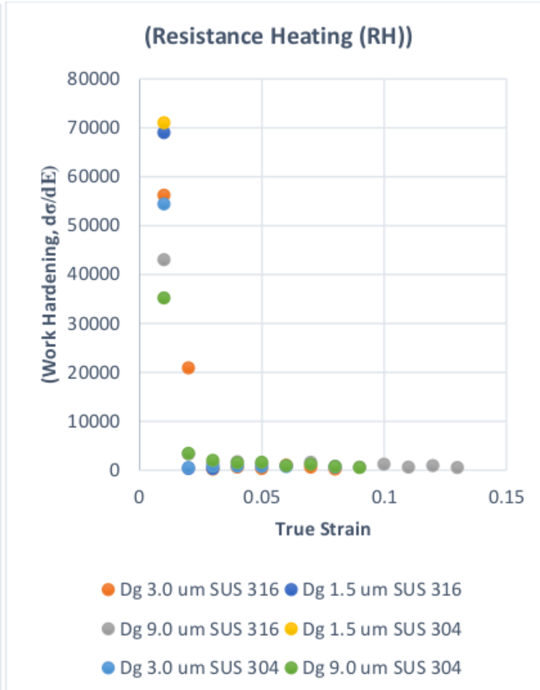
Figure 7. Work hardening behavior in SUS 304 and SUS 316 TMF

According to figure 7A, the work hardening value for SUS 316 increase higher than SUS 304 TMF at room temperature. It means that SUS 316 TMF has more uniform in the deformation distribution in the work piece. Since SUS 316 TMF has more uniform in the deformation distribution, the SUS 316 TMF has more homogeneous than SUS 304 TMF. Because of this, the surface roughness in SUS 304 increase higher than SUS 316 TMF at the same strain level in room temperature.

According to figure 7B, at elevated temperature, the work hardening value in SUS 304 was higher than SUS 316. It means that SUS 304 TMF has more homogeneous than SUS 316 TMF. Thus, the surface roughness in SUS 316 TMF increase higher than SUS 304 TMF at elevated temperature.



A. Room Temperature



B. High Temperature

Figure 8. Slope of work hardening behavior

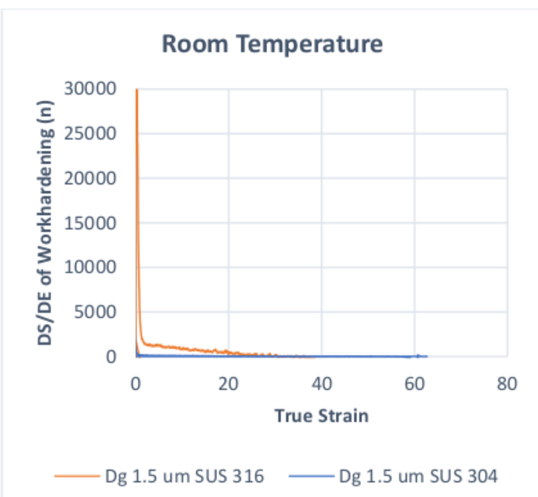


Fig. 9 Room Temperature

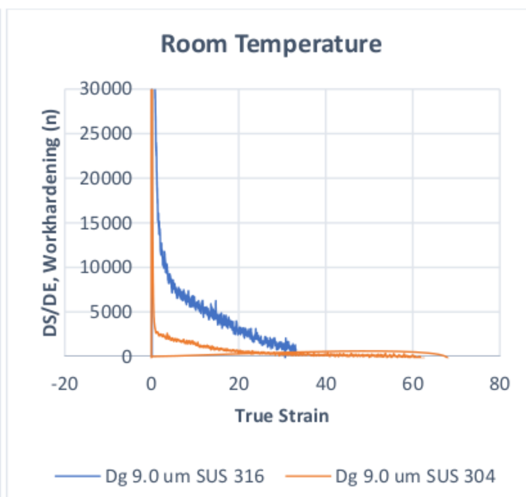


Fig.10 Elevated Temperature

The slope tendency of the work hardening (n) value in SUS 316 was higher than SUS 304 TMF at room temperature, the uniform deformation in work piece in SUS 316 much higher than SUS 304 TMF, thus the SUS 316 become more homogeneous than SUS 304 an surface roughness behavior in SUS 304 become higher than SUS 316 TMF.

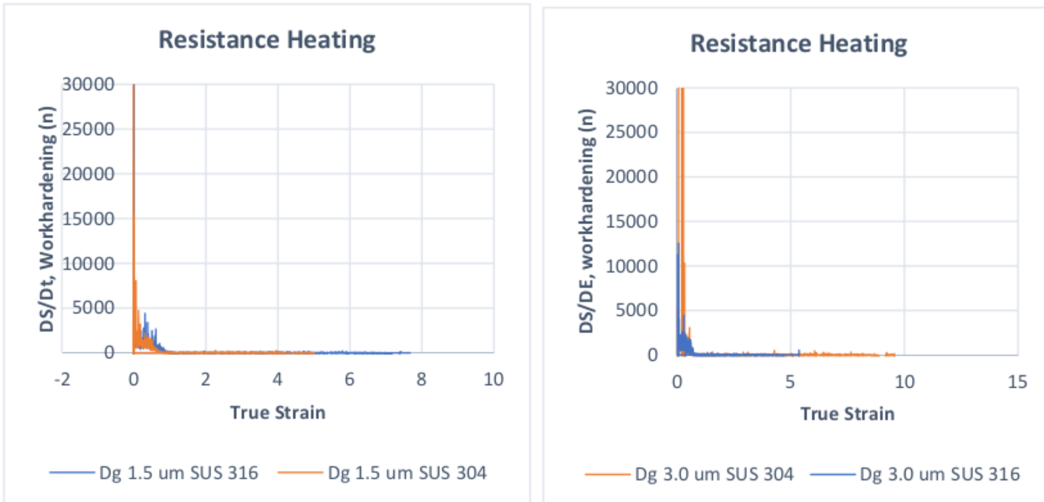


Fig.11

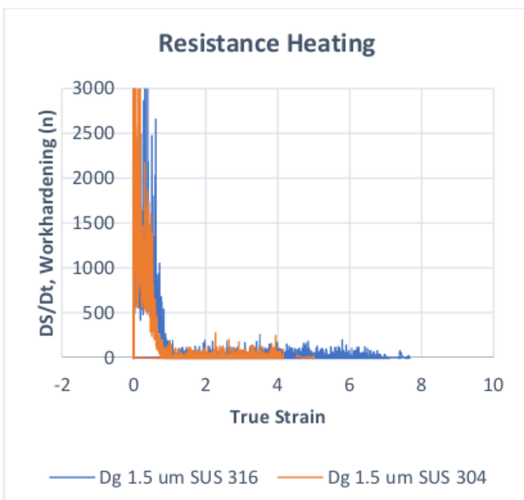


Fig. 12 Fine Grain

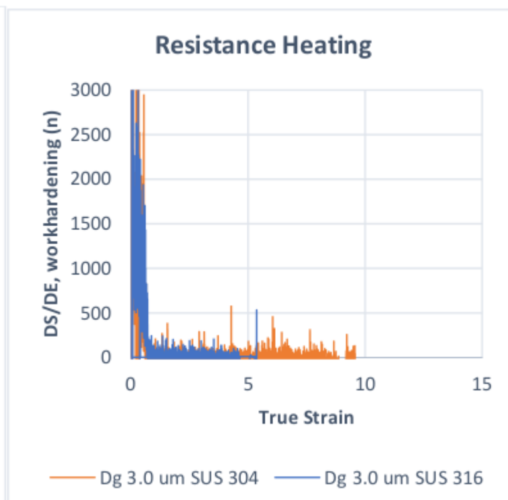


Fig.13 Coarse Grain

The slope tendency between SUS 316 an 304 TMF during resistance heating was quite the same, thus the deformation distribution become quite the same. This condition affect to the similar inhomogeneous grain strength during resistance heating, thus the surface roughness behavior become similar. The surface roughness of SUS 316 become little bit higher than SUS 304, because the slope of SUS 304 was little bit higher than SUS 316 TMF.

In room temperature, work hardening (n) value and the slope of work hardening in SUS 316 was higher than SUS 304. This means the plastic deformation in SUS 316 was more uniform than SUS 304 thin metal foil (TMF). Thus, the

SUS 316 TMF has more homogenous than SUS 304 TMF. Since the SUS 316 TMF more homogeneous than SUS 304 TMF, the increase of surface roughness (ΔRa) in SUS 316 was lower than SUS 304 in the same strain level.

In the resistance heating result, the n value and work hardening slope of SUS 304 were higher than SUS 316. This means the SUS 304 TMF was more homogeneous than SUS 316 TMF. The result showed that the increase of surface roughness (ΔRa) in SUS 304 TMF was lower than SUS 316 TMF at elevated temperature. The previous result of the increasing surface roughness is in good agreement with the n value and slope of n value result.

In room temperature, the surface roughness in SUS 304 TMF increase higher than SUS 316 TMF in coarse grain. The MPT occurred in SUS 304 TMF but not occurred in SUS 316 TMF. The GMO in SUS 316 more inhomogeneous than SUS 304, the MPT spread inhomogeneous in SUS 304, but the increase of surface roughness in SUS 304 was higher than SUS 316 TMF in the same strain level, this means the effect of martensitic phase transformation (MPT) was higher than grain misorientation (GMO) in coarse grain.

The slope of work hardening in SUS 316 TMF was higher than SUS 304 TMF at room temperature as shown in Fig.10. The work hardening (n) value in SUS 316 TMF was higher than SUS 304 TMF at room temperature. The n value and the slope n value tendencies were different in SUS 316 TMF and SUS 304 TMF at room temperature, it means that SUS 316 TMF has more uniform grain strength than SUS 304 TMF. Since SUS 316 TMF has more uniform grain strength than SUS 304 TMF at room temperature, the grain strength in SUS 316 TMF was more homogeneous than SUS 304 TMF. Because the SUS 316 TMF more homogeneous than SUS 304 TMF, the increase of surface roughness in SUS 304 should be higher than SUS 316 TMF. Based on previous result (Aziz et al., 2021), the SUS 304 TMF has more inhomogeneous grain strength than SUS 316 TMF, the SUS 316 TMF has lower increased surface roughness than SUS 304 TMF at room temperature. At room temperature, the GMO spread more inhomogeneous in SUS 316 than SUS 304 TMF, but MPT spread inhomogeneous in SUS 304 while there are no MPT in SUS 316 TMF at room temperature. Based on previous result (Aziz et al., 2021), the increase of surface roughness in SUS 304 TMF was higher than SUS 316 TMF at room temperature, it means that SUS 304 TMF has more inhomogeneous than SUS 316 TMF. In the other words, that MPT has stronger effect on making in homogeneous grain strength than GMO in room temperature.

The increase of surface roughness at elevated temperature was different than room temperature. At elevated temperature, the surface roughness in SUS 316 increase higher than SUS 304 TMF, because no MPT in SUS 304 TMF coarse grain at elevated temperature. The GMO spread more inhomogeneous in SUS 316 TMF than SUS 304 TMF, thus the surface roughness in SUS 316 was higher than SUS 304 TMF. The result of increasing surface roughness in room and high temperature was different, because of the existing MPT between room and elevated temperature was different. At elevated temperature, there are no MPT in SUS 304 TMF coarse grain. The MPT decreased much in fine grain of SUS 304 TMF at elevated temperature. in room temperature, there are a lot of MPT spread inhomogeneous in SUS 304 TMF coarse grain. In room temperature, MPT spread homogeneous in fine grain of SUS 304 TMF. In room temperature the, the increased of surface roughness in SUS 304 was higher than SUS 316 TMF, but, at elevated temperature, the increased of surface roughness in SUS 316 was higher than SUS 304, because no MPT in SUS 304 TMF coarse grain. The work hardening (n) value in SUS 304 was higher than SUS 316 at elevated temperature as shown in Figure 7B. The slope of work hardening (n) in SUS 304 was higher than SUS 316 TMF as shown in Figure 10. It means the deformation distribution in SUS 304 was more homogenous than SUS 316, thus the increasing of surface roughness in SUS 316 was higher than SUS 304 TMF (Aziz et al., 2021).

Dislocation density and % MPT increase proportional with the increasing strain level (K.Kishore et al.,2022) . For the fine grain, the % MPT and dislocation density in a grain become much higher than for the coarse grain, because the slip band intersection probability become much higher in fine grain than in a coarse grain (Tomita et al., Olson and Cohen at al).

Tomota et al, concluded that KAM- value increase proportional with increasing plastic strain. when the plastic strain increase, the grain misorientation that represented by KAM – value increased. The increasing of KAM- value caused by the increasing grain misorientation angle after plastic deformation.

3.1. Quantitative Model

$\sigma = A + B\varepsilon_p^n$

which A is initial stress (MPa),

B is material constant.

ε_p = true strain

n = work hardening coefficient.

ε_p = True strain

The work hardening (n) value increase with increasing grain size (Dg) at room and high temperature. The work hardening (n) in SUS 316 increase higher than SUS 304 TMF at room temperature. The work hardening (n) increase higher for SUS 304 TMF than SUS 316 TMF at high temperature. The initial stress (A) increase with decreasing grain size (Dg) in room and high temperature. The initial stress (A) also increase higher for SUS 304 than SUS 316 TMF at room temperature. The initial stress (A) of SUS 316 increase higher than SUS 304 TMF at elevated temperature. The B is hardening coefficient. The hardening coefficient in SUS 304 is 940 MPa and SUS 316 is 950 MPa. Thus, the hardening coefficients were quite similar between SUS 304 and SUS 316 TMF. The ε_p is true strain of SUS 304 and SUS 316 TMF. And n is work hardening value of SUS 304 and SUS 316 TMF.

$\varepsilon_p = C.P_d$

where C is material constant, P_d is a density.

when the true strain increase, the dislocation density increase, also when the true strain decrease, the dislocation density also decrease.

Fv, MPT = C. P_d (SUS 304).

Fv,MPT means volume fraction of MPT. From the previous research, when the MPT increase, the dislocation density also increase, when the MPT decrease, the dislocation density also decrease (Tomita et al.).

Fgmo = C. P_d (SUS 316)

Which Fgmo means the volume fraction of GMO in SUS 316. When the GMO increase, the dislocation density increase in SUS 316, when the GMO decrease, the dislocation density decrease in SUS 316 TMF.

n= C. (GMO +FvMPT) (SUS 304).

n means work hardening in thin metal foils. When the GMO increase homogeneous and the MPT increase homogeneous, the work hardening decrease and we call it n_1.. When the GMO increase inhomogeneous and MPT decrease (disappear) we call it n_2, When the MPT increase inhomogeneous and GMO increase inhomogeneous, we call it n_3. The result is $n_3 > n_2 > n_1$.

n= C.Fgmo (SUS 316). When GMO increase homogeneous, we call it n_4. When GMO increase inhomogeneous, we call it n_5. The result is $n_5 > n_4$. The result also $n_3 > n_5 > n_2 > n_1 > n_4$.

Ra = (Fmpt + Fgmo) x (F inhomogeneous)xDg/t

Which Ra means surface roughness, Fmpt means volume fraction of MPT, Fgmo means volume fraction of GMO, F inhomogeneous means volume fraction of inhomogeneous GMO or inhomogeneous MPT, Dg means grain size an t is thickness. The volume fraction of inhomogeneous (F inhomogeneous) scale since 0 until 1 (0 – 1). When the inhomogeneous of MPT and GMO increase, the surface roughness increase, the increasing surface roughness increase with increasing grain size (Dg). The increasing surface roughness caused by the increasing inhomogeneous of MPT and inhomogeneous of GMO called Ra_1, the increasing surface roughness caused by inhomogeneous MPT and zero GMO called Ra_2, the increasing surface roughness, the increasing of surface roughness caused by zero MPT and inhomogeneous GMO called Ra_3, the surface roughness caused by homogeneous GMO and MPT called of Ra_4. From the previous research, the value of Ra behaviors are Ra1>Ra2>Ra3>Ra4.

3.2. Function of Inhomogeneous

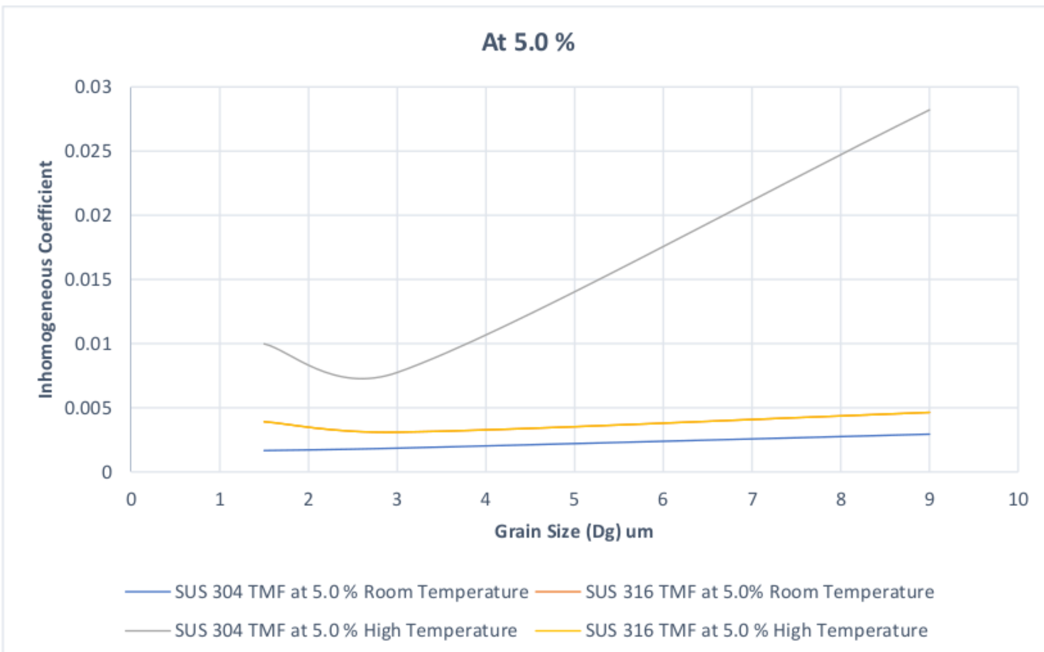


Fig. 14

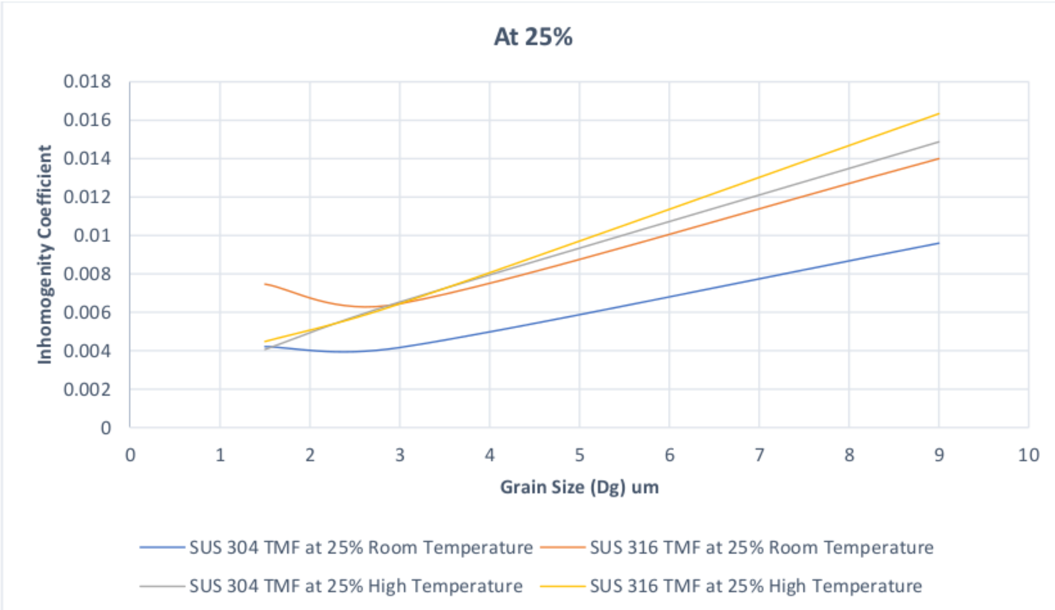


Fig.15

At room temperature, the slope of SUS 304 was higher than SUS 316 TMF but at elevated temperature (resistance heating), the slope of SUS 304 and SUS 316 were similar.

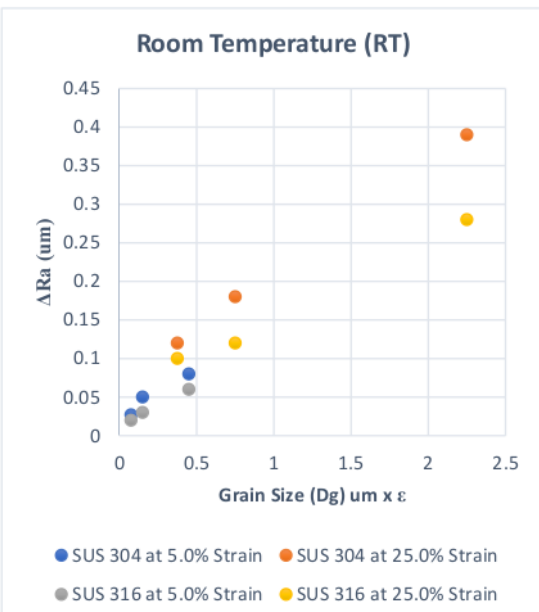


Fig. 16 Room Temperature (RT)

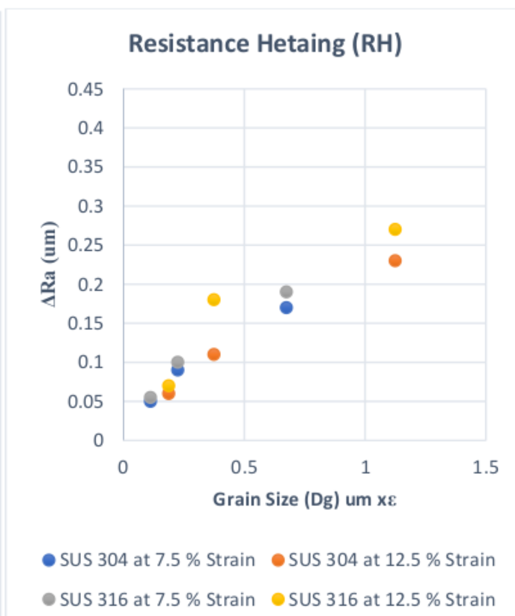
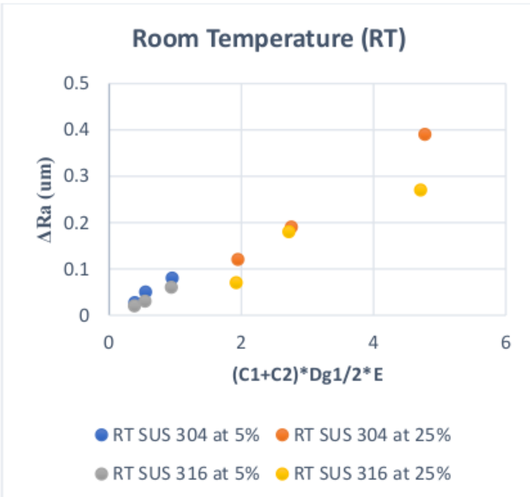


Fig. 17. Resistance Heating (RH)

The slope for SUS 304 TMF in RT was higher than SUS 316 TMF. The slope for SUS 304 TMF at ET was similar wit SUS 316 TMF. The increasing surface roughness (ΔRa) in SUS 304 TMF was higher than SUS 316 at RT, but the ΔRa at ET in SUS 304 was similar than SUS 316 TMF.



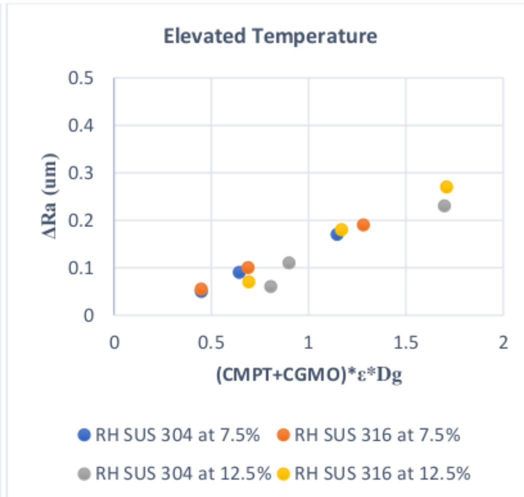


Fig. 18 Room Temperature (RT)

Fig. 19. Elevated Temperature (RH)

Based on figure 18, the slope tendency in SUS 304 coarse grain was much higher than SUS 316 coarse grain. The MPT spread inhomogeneous in SUS 304 in coarse grain that affect to higher inhomogeneous grain strength in SUS 304 than SUS 316 TMF coarse grain. For fine grain, the tendency of slope is similar both in SUS 304 and SUS 316 TMF, because the MPT spread homogeneous.

The fig. 18 show that the SUS 304 TMF has higher slope at high strain level, but for low strain level, the slope was similar. After resistance heating (RH) or at elevated temperature (E.T), the slope was similar at low strain and high strain level for 1,5 um ; 3,0 un ; 9,0 um. MPT decrease much at ET, thus the inhomogeneous grain strength at ET both in SUS 304 and SUS 316 determined by the grain misorientation (GMO). The slope tendency become similar at ET.

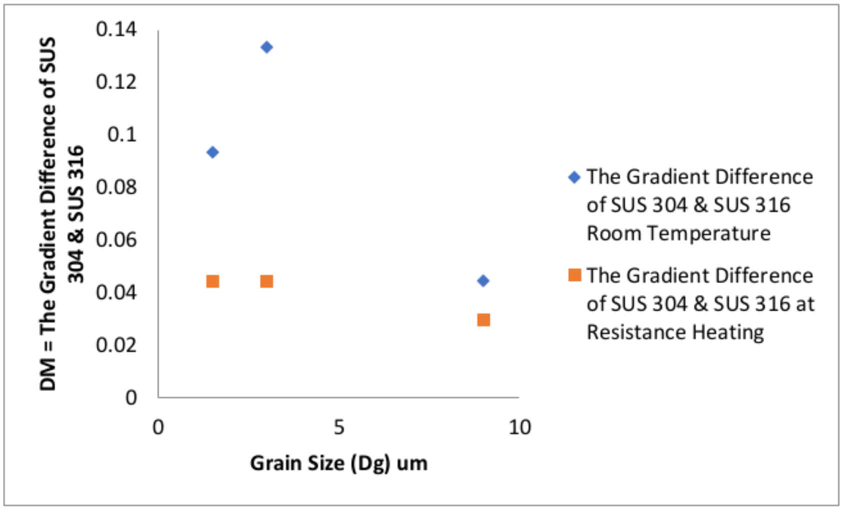


Fig. 20. The Difference of Gradient in SUS 304 and SUS 316 Both in R.T. and E.T.

The different of gradient between SUS 304 and SUS 316 in RT was higher than ET, because in room temperature consist of MPT in SUS 304 TMF and no MPT at ET.

Conclusion

1. MPT has stronger effect than GMO on showing surface roughness after tensile test with the same strain level.
2. In room temperature, the SUS 304 TMF showed higher surface roughness than SUS 316, but at elevated temperature, the SUS 316 TMF showed higher surface roughness than SUS 304 TMF in the same strain level.
3. The slope behavior in room temperature was different which SUS 304 was higher than SUS 316, but the slope in high temperature was quite similar.
4. In room temperature, SUS 304 more inhomogemeous than SUS 316 but at high temperature, the inhomogeneous grain strength was similar.

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