Effect of Surface Nano-crystalline Layer Formed by Heavy Plastic Deformation Process on Rolling Contact Fatigue

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This study developed a deformation process to form a uniform nano-crystalline layer with relatively high thermal stability that can retain even after an induction heating and quenching process on a surface of cylinder-shaped sample. The effect of the surface nano-crystalline layer on rolling contact fatigue life of carbon steels (JIS S45C and S55C) was investigated. The sample with the surface nano-crystalline layer showed lower friction coefficient under cylindrical rolling contact condition comparing to that without the layer. The rolling contact fatigue life was extended to 4 times higher cycles by forming the nano-crystalline layer. It is presumable that the improvement of a rolling contact fatigue is owing to not only the high hardness but also the reduction of friction coefficient during the test followed by a suppression of dynamic tempering softening and variation of stress distribution.

KEY WORDS: rolling contact fatigue; nano-crystalline; heavy plastic deformation; friction coefficient.

1. Introduction

In rolling elements such as bearings, gears, and camshafts, where rotational motion and significant load are applied simultaneously, materials are subjected to high continuous contact pressure, which result in rolling contact fatigue (RCF). The RCF is becoming more important problem from points of view of both durability and efficiency with an advancement of rolling elements. In ideal case (i.e., pure rolling), the failure in RCF occurs through materials fatigue, in which contact stress is governed by Hertzian theory. Therefore, damage in machinery parts results from operation is substantially provoked by wear and/or fatigue in the surface and subsurface. Such phenomena are heavily influenced by lots of factors such as contact pressure, materials constant, microstructure, and surface roughness, etc. From the microstructural aspect, the conventional way to improve RCF life of steels is performed through thermal quenching after carburizing or nitrocarburizing. Coating techniques such as thermal splaying, physical vapor deposition, and chemical vapor deposition are also commonly used process to achieve improved RCF life.1) Furthermore, it was reported that grain refinement of prior austenite as well as martensite laths can also give improved RCF life in bearing steels.2) In the case of RCF under lubrication, characteristic of a lubrication film formed by an interaction between lubricant molecules and sample surface should be also important factor to improve RCF life.

In the past few decades, heavy plastic deformation techniques, such as accumulative roll-bonding,3) high-pressure torsion,4) and equal channel angular pressing,5) which can introduce theoretically infinite plastic strain into a sample, have been developed. Consequently, fabrication of a bulk material with a grain size of below 1 μm, which called ultrafine grained material, become possible. Many literatures about wear properties of ultrafine grained materials have been reported as reviewed by Gao et al.6) For instance, in the steel material case, Wang et al. have reported the wear property of nano-crystalline, which is fabricated by a surface mechanical attrition treatments (SMAT) on a surface of a low carbon steel, measured by a ball-on-disk method under unlubricated condition.7) They found that the surface nano-crystalline layer gives higher wear property as well as lower friction coefficient. Huang et al. and Kato et al. have also reported a decrease of wear rate8,9) and friction coefficient8) with decreasing grain size under unlubricated fric-
tion test. In contrast to above, decrease of wear resistance by grain refinement has been also reported in Al alloys and steels, which have been also performed under unlubricated condition. Therefore, it is reasonable to think that nano-crystalline structure provides positive effect for wear and friction property under specific conditions.

Adachi et al. have found that, employing the ball-on-disk test, the nano-crystalline structure holds interesting advantage on reducing friction coefficient under oil-lubricated condition using the pure Fe samples prepared by using the ion beam sputtering. The observations using the frequency modulation atomic force microscopy, which can visualize adsorption of oil molecules on the surface of a sample, have shown that the increase of the fraction of grain boundary is important to form thick absorbed film. Previous theoretical calculations have shown that an atom or molecule is preferentially adsorbed at disordered atomic configuration in the vicinity of lattice defects such as grain boundary and vacancy lattice defects have relatively high absorbability of oil molecules. Consequently, friction coefficient during the ball-on-disk test was reduced by the presence of nano-crystalline.

Recently, we have developed a new surface heavy plastic deformation process called Surface Nanostructured Wearing (SNW). In the SNW process, as shown in Fig. 1, a lateral face of a tipping tool is pressed to a turning cylindrical sample in a lathe at a certain load and rotation speed, and then the tipping tool is moved along rotation axis of the sample under oil cooling. This process is similar process to burnishing but conditions such as pressing load are heavier than the tipping tool is moved along rotation axis of the sample under oil cooling. In the process, as a pressing load and rotation speed is quite high, surface temperature of a sample in the SNW process. In the process, as a pressing load and rotation speed is quite high, surface temperature of a sample in the SNW process. Consequently, microstructure of the sample significantly refined by dynamic recrystallization because of high Zener-Hollomon parameter, followed by a formation of nano-crystalline structure to the depth of around 10 μm from the sample surface. Transformation from heavily deformed austenite can also contribute to the formation of nano-crystalline structure. Although a region where nanocrystalline are obtained is limited at a sample surface contrary to the above-mentioned heavy plastic deformation techniques, the SNW process has an advantage in a simplicity of the process which applicable to industrial production line to improve mechanical property of cylindrical material through grain refinement. Considering the practical use of cylindrical material with the nano-crystalline structure, the RCF life is becoming very important to ensure the durability.

From the perspective of RCF under oil-lubricated condition, not only high hardness but also low friction coefficient is important parameter to improve RCF life as described in the contact fatigue life prediction model proposed by Kudish and Burris. In this study, we focused on the effect of nano-crystalline structure, which gives lower friction coefficient because of the high absorbability of oil molecules, the RCF life of the sample prepared by the SNW process was investigated. Prior to the RCF test, using the traction test, we verified the effectiveness of the surface nano-crystalline layer formed by the SNW process on reducing friction coefficient under cylindrical rolling contact condition. Then, the effect of the surface nano-crystalline structure on a RCF life under oil-lubricated condition has been investigated. The effect of reduced friction coefficient on RCF life was evaluated from perspectives of the subsurface shear stress distribution and the dynamic tempering softening induced by heat generation.

2. Experimental Procedure

2.1. Traction Test

Material used for the traction test is JIS S55C. In order to adjust the Vickers hardness to be 4 GPa, the material was quenched and tempered under the condition shown in Fig. 2. Thus, the sample has an initial microstructure of tempered martensite. The rod-shape sample was subjected to the SNW process at a load, revolution rate, and feeding speed of 1 575 N, 1 600 rpm, and 0.03 mm/rev, respectively, and the sample was subsequently subjected to the rapid heating and quenching using Super Rapid Induction Heating and Quenching (SRIQ) process; this sample is referred to as SNW+SRIQ sample. In the SRIQ process, the sample was rapidly heated with a heat up time of 0.6 s and water quenched from quenching temperature of 1 173 K without holding time to form hardened surface and subsurface. The sample without the SNW process was also prepared as comparison (SRIQ sample). The condition of the SNW process was optimized to minimize the increment of surface roughness during the process. The arithmetic average roughness of the SNW+SRIQ and SRIQ samples were

![Fig. 1. Overview of Surface Nanostructured Wearing (SNW) process developed by the authors. (Online version in color.)](image1)

![Fig. 2. Heat treatment condition to adjust the Vickers hardness to be 4 GPa.](image2)
In order to confirm the presence of surface nano-crystalline structure, the cross-section of the sample was polished and etched to visualize prior austenite grain boundary using picric acid solution, and the microstructure of the samples was observed using optical microscopy (OM). Two disk-shaped samples with a thickness of 8 mm were cut out from the SNW-processed rod as shown in Fig. 3(a-1) and were subjected to the traction test. Traction test was performed under oil lubrication using ring-on-ring traction machine (Phoenix Tribology Ltd., TE54). A material for a mating roller for the traction test is the case hardened JIS SCM420 with a radius and thickness of 49 and 10 mm. In order to avoid stress concentration owing to the sharp edge of the mating roller, the large curvature with a radius of 300 mm was formed on the surface of the mating roller. Nissan Matic D automatic transmission fluid with temperature of 353 K was used as lubricant oil. A normal load $F_N$, rotation speed of the sample, and slip ratio for the traction test are 300 N, 1 500 rpm, and -40%, respectively. As the widths of the wear tracks formed after the traction test were 1–2 mm, contact pressure during the traction test was estimated to be 1.0–1.5 GPa on the basis of Hertzian theory. Traction force $F_t$ was in situ measured during the test by using a load cell. Friction coefficient obtained by the traction test $\mu_t$ is here defined as $F_t/F_N$.

### 2.2. Rolling Contact Fatigue Test

Material used for the RCF test is JIS S45C steel. As with the traction test sample, the material was also quenched and tempered to obtain initial Vickers hardness of 4 GPa under the condition shown in Fig. 2. The SNW process was performed using the sample shape shown in Fig. 3(a-2) at a revolution rate and feeding speed of 1 600 rpm and 0.03 mm/rev, respectively, which is referred to as SNW sample. Owing to the difference of work hardening rate between S45C and S55C during heavy plastic deformation, the S45C sample for the RCF test requires a slightly lower load (1 500 N) to obtain nano-crystalline structure comparing with the traction test sample (S55C). The samples with and without the SNW process (SNW+SRIQ and SRIQ samples) were subjected to SRIQ process with $T_o$ of 1 223 K and $t_o$ of 0.3 s. The samples with and without the SNW process have $R_h$ of 1.5 and 0.4 $\mu$m, respectively. Vickers hardness ($H_V$) of each sample was measured with a load, and holding time of 0.98 N and 15 s, respectively. As shown in Fig. 3(b), a hardness of outermost surface was measured by indenting the surface from radial direction of the samples. The sample was cut along A–A’ line, and a depth profile of hardness was also investigated by measuring the cross-sectional hardness along z (depth) axis. Microstructure of samples were observed using OM and scanning electron microscope (SEM). For the OM and SEM, the samples were etched using 5% nital prior to the observations. Residual stress in both circular and axis directions of the sample was measured by X-ray diffraction (PROTO Manufacturing Inc., LXRD) using Cr-Kα radiation having a beam size of $\phi$ 1 mm. In order to measure residual stress as a function of $z$, a part of sample surface of $4 \times 4 \text{ mm}^2$ was electropolished by using the electrolyte contains perchloric acid, ethanol, and distilled water. The RCF life of each sample was measured by roller pitting machine (Komatsu Engineering Corp., RP-201), at a rotation rate of 1 500 rpm at 353 K under lubrication (Nissan Matic D). The case hardened JIS SCM420H with a radius of 65 mm and thickness of 18 mm, which has $H_V$ of 7.5 GPa to the z of 50 $\mu$m, was used as loading-roller in the RCF test. The surface of the loading roller was machined to have a large curvature with a 300 mm radius as with the traction test. The slip ratio in the RCF test is -40%. By changing a load during the RCF test, RCF lives at two different magnitude of contact pressures $p_0$. 2 500 and 3 000 MPa were investigated. On the basis of Hertzian theory, $p_0$ is given by,

$$p_0 = \left( \frac{PE}{\pi R} \right)^{1/2}$$  \hspace{1cm} (1)

where $P$ shows a load per unit length. Contact modulus $E'$ and effective radius $R$ are given by $E' = \left( \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)^{-1}$ and $R = (1/R_1 + 1/R_2)^{-1}$, respectively. The subscript numbers...
1 and 2 denotes a sample and a loading roller, respectively. Since the iron-based alloys are commonly used for both the sample and roller, it is reasonable to assume that these two have equivalent young’s modulus $E$ and Poisson ratio $\nu$. Here, assuming that the sample has uniform elastic property, $E$ and $\nu$ of polycrystalline steel ($E = 205$ GPa and $\nu = 0.3$) were used for the calculation. Figure 4 shows the distribution of principal shear stress $\tau_1$ in the $x$-$z$ plane calculated on the basis of Hertzian theory, where $x$ shows the axis perpendicular to rotation and $z$ axes (see Fig. 3(b)). The vertical and horizontal axes of the figure were normalized by $p_0$ and $a$, respectively. Here, $a$ shows a contact half-width along $x$ axis, which is given by,

$$a = \left(\frac{4PR}{\pi E}\right)^{1/2},$$

which can be estimated by Hertzian theory. Maximum $\tau_1 (\tau_1^{\text{max}})$ is 0.300$p_0$ and located at 0.78$a$. The $a$ at $p_0$ of 2 500 and 3 000 MPa were estimated to be 285 and 430 $\mu$m, respectively. It should be noted that this $\tau_1$ distribution is of static state where the effect of tangential force is not considered.

3. Results

3.1. Variation of Friction Coefficient under Cylindrical Rolling Contact

Microstructures of the JIS S55C samples for the traction test observed by the SEM are shown in Figs. 5(a) and 5(b). It can be clearly seen that the SNW+SRIQ sample has fine prior austenite grain size in the vicinity of surface while the SRIQ sample has coarse grains. More detailed microstructure formed by the SNW process can be found in section 3.3. The higher $HV$ at the outermost surface in the SNW+SRIQ sample also indicates the presence of nanocrystalline layer (Fig. 5(c)).

Figure 6 illustrates $\mu_T$ of the samples during the traction test as a function of testing time $t$. The traction test has been repeated three times for each sample, and average values are plotted in the figure. The figure indicates that the SNW+SRIQ sample having fine grain shows lower $\mu_T$. This result is in good agreement with previous ball-on-disk results, meaning that grain refinement is effective to reduce $\mu$ irrespective of the contact condition (i.e., ring-on-ring or ball-on-disk). The high $HV$ of the nanocrystalline layer can be a factor decreasing $\mu$ during the RCF test. As reviewed by Gao et al., however, grain refinement can induce both decrease and increase of $\mu$ depending on the test conditions in the case of un lubricated condition. We have also reported that the pure iron
samples having different hardness showed comparable μ irrespective of grain size under the lubrication using the oil which forms no tribofilm. 11) The contribution of HV on μ is therefore uncertain in this study. Okada et al. have recently reported the reduction of μ by applying the SNW process to the vacuum carburized JIS S20C having an initial microstructure of pearlite. 23) They have investigated the surface microstructure after the traction test by using the TOF-SIMS analysis and found that the Fe–O–P compound formed by chemical reaction between the sample and oil molecules, which is one of the types of tribofilms having an effect to reduce μ, was homogeneously formed on the surface of the SNW-processed sample. The Fe–O–P compound formed in the sample without the SNW process was inhomogeneous. This trend suggests that the formation of the tribofilm is accelerated by the existence of grain boundary because of high absorbability of atomic structure in the vicinity of grain boundary. 15,16) In the case of ball-on-disk test, it has been demonstrated that the presence of lattice defects is also effective to form thick chemisorbed film, which is another type of tribofilms. 11,12,18) Regarding above results, it can be concluded that the nano-crystalline layer formed on the surface of material effectively works to reduce μ by forming tribofilm on the surface under cylindrical rolling contact condition.

3.2. Vickers Hardness Profiles after the SNW and SRIQ Processes

Figure 7 shows the HV profiles in the SNW and SRIQ samples as a function of z. The SRIQ treated sample has a martensitic hardened layer which formed during the SRIQ with HV of 7 GPa to the z of around 800–900 μm (SRIQ hardened layer). By using the SNW process, the outermost surface reached higher hardness (HV = 9.0 GPa) than the SRIQ sample owing to the formation of heavily deformed layer on the surface. Depth of this hardened layer induced by the SNW process is limited to the outermost surface. It should be noted that the softening region can be seen in the SNW-processed sample at z ≤ 300 μm, which is formed by tempering result from the heat generation during the process. In an ideal rolling contact situation without tangential force, the τz, max is located at subsurface region (z = 0.78a) as shown in Fig. 4. In the case of our RCF conditions, the location of τz, max is close to the tempered softening region under both p0 levels; the z with τz, max are estimated to be 221 and 334 μm at p0 of 2 500 and 3 000 MPa. It is therefore suspected that the tempered softening region may provoke negative effect and the shallow hardened layer formed by the SNW process shows no effect for the RCF life. In order to overcome such problem in the SNW-processed sample, the heat-and-quenched sample using the SRIQ after the SNW process was prepared (SNW+SRIQ sample), whose HV profile is also shown in Fig. 7. The SNW+SRIQ sample also had the SRIQ hardened layer to the same depth as the SRIQ sample. Interestingly, the hardened layer formed by heavy plastic deformation during the SNW process kept high hardness value even after the heat-treatment by the SRIQ process.

3.3. Microstructure Formed by the SNW and SRIQ Processes

SEM micrographs of the SNW and SNW+SRIQ samples are shown in Fig. 8. Each sample for the SEM observation was cut, and microstructure in longitudinal section was observed. It can be seen that, in the SNW sample, the grains were refined to a grain size of below 1 μm in the entire observation area. Furthermore, the nano-crystalline layer was formed to the z of ≈ 5 μm. This layer corresponds to the hardened layer induced by the SNW process, which has HV of 9.0 GPa (see Fig. 7). In the SNW+SRIQ sample, as was confirmed in the hardness test (Fig. 7), the nano-crystalline layer retained even after heated up to 1 123 K in the SRIQ while coarse martensite lath, which have an identical HV value to the SRIQ sample without the SNW process, was formed in the z of > 8 μm. This result suggests that the nano-crystalline layer formed using the SNW process have high stability against the high atmospheric temperature. Although investigation of underlying mechanism of high thermal stability of the nano-crystalline layer is not the purpose of study, it can be expected that the stabilization of nano-crystalline is related to the solute elements such as C and contaminated O during the SNW process. Chookajorn et al. have reported that the segregation of solute atoms, which can reduce grain boundary energy from unalloyed condition, resulting in the stabilization of nano-crystalline. 20) Heavy plastic deformation of tempered martensite structure can cause not only significant grain refinement but dissolve of carbide. When this microstructure is heated, since the grain boundary have lower solution energy of C compared with bcc iron matrix, 25) C atoms may segregate to nearby grain boundaries. The segregation of C atoms at grain boundary has been experimentally observed in the heavily deformed iron and steel by using the mechanical ball milling. 26,27) Similar to our results, the nano-crystalline formed by the mechanical ball-milled Fe have shown relatively high thermal stability during the sintering process, and the reduction of grain boundary energy was suggested as the reason of stabilization in the literature. 27) It is therefore presumable that the nano-crystalline was stabilized by the segregation of C which causes the reduction of grain boundary energy. At current state of this study, there is no evidence to prove above hypothesis for nano-crystalline stabilization, which
3.4. Residual Stress Introduced by the SNW and SRIQ Processes

It is widely known that compressive residual stress suppresses a crack formation and propagation, which can increase a RCF life of a material. Figure 9 shows variation of residual stress with \( z \) in the SRIQ samples with and without the SNW process. In both circular and axis directions, the magnitude of residual stress increased with \( z \), meaning that the maximum compressive residual stress located at subsurface region. In the sample after the SRIQ, both thermal gradient and martensitic transformation are thought to be the origin of residual stress. The obtained residual stress distribution can be formed when the effects of thermal stress and transformation stress are combined.\(^{28}\) The magnitude of residual stress is not much affected by the presence of the surface nano-crystalline layer formed by the SNW process. Therefore, contribution of the residual stress on the RCF life is regarded as equal between the samples prepared in this study.

3.5. Rolling Contact Fatigue Lives in the SRIQ and SNW+SRIQ Samples

The RCF lives of the SRIQ samples with and without the SNW process at \( p_0 \) of 2 500 and 3 000 MPa are shown in Fig. 10. In both the stress levels, the SNW+SRIQ sample showed longer RCF life compared with SRIQ sample; the SNW+SRIQ sample had 6 and 4 times longer RCF life at \( p_0 \) of 2 500 and 3 000 MPa, respectively. Morphology of wear tracks formed during the RCF test was investigated by the laser microscope. Figure 11(a) illustrates the depth profiles of wear tracks formed during the RCF test at \( p_0 \) of 2 500 MPa scanned perpendicular to wear track. As clearly seen in the profiles, the depth of wear track significantly decreased in the sample with the SNW process. The maximum depth of wear tracks in each sample are summarized in Fig. 11(b). The depth of wear track was decreased by 70 and 60\% by forming nano-crystalline layer at \( p_0 \) of 2 500 and 3 000 MPa, respectively; the SNW process effectively works to improve wear resistance of the samples. It is interesting to note that the SNW+SRIQ sample showed longer RCF lives
in spite of the higher $R_a$ (see section 2.2.), suggesting that the presence of surface nano-crystalline layer is effective enough to cancel the negative effect of $R_a$ on RCF life.

3.6. Cracks Formed during the Rolling Contact Fatigue Test

Each sample after the RCF test was cut along the wear track (see Fig. 12(a)) and cross-section of the sample was observed by the SEM and OM. The white and gray regions which were formed owing to the difference in a degree of corrosion during etching can be seen. Thickness of the white region was roughly estimated to be 800 μm from the images, which corresponds to the thickness of the martensitic hardened layer formed by the SRIQ process (Fig. 7). Considering the higher corrosion resistance of an as-quenched martensite comparing with a tempered martensite, it can be concluded that the white and gray region are the martensitic layer and matrix, respectively. In the interface between the martensitic layer and matrix, darkest contrast can be seen. This is owing to the tempered softening (shown in Fig. 7 as dotted circle) during the SRIQ process. In case of the SRIQ sample, the cracks formed parallel to rolling direction were observed at the $z$ of around 200 and 900 μm after the RCF test as shown as black triangle marks. The cracks formed at the $z$ of 200 μm were observed at both $p_0$ (Figs. 12(b) and 12(d)). Another crack at the $z$ of 900 μm formed in the SRIQ sample at $p_0$ of 3 000 MPa. In contrast, from the observation of the SNW+SRIQ sample, cracks could not be observed in subsurface at both $p_0$ levels.

4. Discussion

The improvement of RCF life was achieved by forming surface nano-crystalline layer using the SNW process (Fig. 10). The high surface $HV$ in the SNW sample may suppress an initiation of a surface crack and improve a RCF life. In the case of the sample without surface nanocrystalline layer (i.e., SNW+SRIQ sample), however, the cracks were formed at a much deeper depth comparing with the surface nanocrystalline layer, meaning that a crack preferentially initiates at surface rather than surface under the condition tested. It is therefore presumable that the nano-crystalline layer contributed for the improvement of RCF life by other factor apart from the high hardness. Although the residual stress is a possible factor to improve an RCF life by suppressing crack formation, no clear difference could not be seen between the samples used in this study (Fig. 9). As shown in Fig. 12, it was revealed that the surface nano-crystalline layer effectively works to suppress formation of a crack at $z$ of both 200 and 850 μm. The traction test results in this study (Fig. 6) and previous work 11,12,18,23 show that the nano-crystalline structure causes reduction of $\mu$ during a friction test. As described in following sections, it can be considered that the reduction of $\mu$ caused by grain refinement is important to suppress crack formation at both depths.

4.1. Effect of Friction Coefficient on Shear Stress Distribution under Cylindrical Contact

In order to discuss the effect of $\mu$ on the formation of cracks during the RCF test, it is important to know the stress distribution in the surface and subsurface regions considering the contribution of a tangential force which works reflecting $\mu$ value. Hertzian theory covers the influence of tangential force on subsurface stress distribution under cylindrical contact, and Ewen have expressed stresses at general point $(x, z)$, which are given by,

$$\sigma_x = -\frac{p_0}{a} \left[ m - 2z + 2\mu(x - n) + m \frac{z^2 + n^2}{m^2 + n^2} + \mu n \frac{z^2 - m^2}{m^2 + n^2} \right],$$

$$\sigma_z = -\frac{p_0}{a} \left[ m - m \frac{z^2 + n^2}{m^2 + n^2} - \mu \frac{z^2 - m^2}{m^2 + n^2} \right],$$

$$\tau_{xz} = -\frac{p_0}{a} \left[ \mu(m - 2z) - n \frac{z^2 - m^2}{m^2 + n^2} + \mu m \frac{z^2 + n^2}{m^2 + n^2} \right].$$

where $m$ and $n$ are defined by,
From Eqs. (3) and (4), distribution of $\tau_1$ in $x$-$z$ plane with considering the effect of $\mu$, can be derived. Figure 13 illustrates the change in $\tau_1$ distribution with increasing $\mu$. The $x$- and $z$- axes were normalized by $a$ in the same way as Fig. 4. The calculated $\tau_1$ was normalized by $p_0$ and is shown as color and contour maps. Location of the point having maximum $\tau_1$ ($\tau_1^{\text{max}}$) is shown as a cross mark in each map. At $\mu = 0$, $\tau_1^{\text{max}}$ is estimated to be 0.300$p_0$ and located at $z = 0.78a$, which is identical to the static normal contact shown in Fig. 4. As described in section 3.2., the $z$ with $\tau_1^{\text{max}}$ ($z^{\text{max}}$) at $p_0$ of 2 500 and 3 000 MPa with $\mu = 0$ are estimated to be 221 and 334 $\mu$m, respectively. Figure 13 demonstrate that the location of $\tau_1^{\text{max}}$ gradually approaches toward surface with increasing $\mu$, and the outermost surface becomes $\tau_1^{\text{max}}$ point at $\mu$ of between 0.3 and 0.4. This trend is in good agreement with previous reports. 33,34) Considering the experimental fact...
that the cracks during the RCF test are formed at subsurface rather than the outermost surface, the $\mu$ during the RCF test is expected to be below 0.3.

### 4.2. Cracks Formed at a Depth of around 200 $\mu$m

The cracks were formed at $z = 200$ $\mu$m regardless of the magnitude of $p_0$ and observed only in the SRIQ sample. The depths correspond to 0.70$a$ and 0.60$a$ under $p_0$ of 2 500 and 3 000 MPa, respectively. As mentioned in previous section, the $z_{max}$ at $\mu = 0$ is located at 0.78$a$; $z = 221$ and 334 $\mu$m at $p_0$ of 2 500 and 3 000 MPa, respectively, showing that the cracks were formed at slightly shallower $z$ than the $z$ expected from static normal contact. This trend can be well explained from the $\tau_1$ distribution obtained by the above analysis. As demonstrated in Fig. 13, the $z_{max}$ approaches towards surface from 0.78$a$ with increasing $\mu$. Assuming that the crack formation occurs at $z_{max}$, the $\mu$ during the RCF test ($\mu_R$) at $p_0$ of 2 500 and 3 000 MPa were estimated to be 0.13 and 0.20, respectively. The $\mu_R$ value under $p_0$ of 3 000 MPa showed higher value than that under $p_0$ of 2 500 MPa. This difference can be qualitatively explained on the basis of Stribeck curve. Considering the occurrence of wear during the RCF test (Fig. 11) and the $\mu_R$ values, the lubrication condition during the RCF test is mixed lubrication regime where the friction occurs through the combination of rubbing of surface and viscous dissipation. In this regime, $\mu$ increases with decreasing the Hersey number $\eta N T$, where $\eta, N,$ and $T$ show viscosity, rotational speed, and load, respectively. As the higher $p_0$ lead to increase of the Hersey number, $\mu_R$ is expected to increase. The increase of $\mu$ also induces increase in the magnitude of $\tau_{1 max}$ as shown in Fig. 13. Based on the Lundberg-Palmgren theory, which is used for a prediction of fatigue life in International Standards, fatigue life $N$ can be expressed as,

$$N = C \left( \frac{z_{max}}{z_{1 max}} \right)^{\eta T}, \quad \text{.................................. (5)}$$

where $C, \eta, T, l,$ and $e$ are material’s constant, depth component, length of the track, life exponent, respectively. From the model, it can be seen that the increase of $\mu$ causes negative effect in terms of both $\tau_{1 max}$ and $z_{max}$. Considering that the SNW+SRIQ sample showed lower $\mu_1$, it is reasonable to conclude that the surface nano-crystalline layer contributes to improve RCF life of the sample.

In addition to the variation of $\tau_1$ distribution affected by $\mu$, heat generation during the RCF test should also be important factor because a high rotation speed with a certain slip ratio during the RCF test can lead to the increase of surface temperature of a sample by friction. As the heat generation can induce dynamic tempering softening during the RCF, and the fatigue at the softened part becomes significant. Figure 14(a) shows the HV profiles of the samples as a function of $z$ before and after the RCF test. Softening owing to the heat generation during the RCF test was observed in both the samples. Except for the outermost surface, the degree of softening became high with approaching to the surface in both samples. However, despite the difference of hardness distribution between the samples before the RCF test could be seen only in the outermost surface (Fig. 7), the degree of the softening was approximately 0.5 GPa small in the SNW+SRIQ sample comparing to the SRIQ sample. It is noteworthy that, since the SNW+SRIQ sample has 4 times longer RCF life than the SRIQ sample, the SNW+SRIQ sample was exposed to generated heat much longer time comparing with the SRIQ sample. This result suggests that, as the material used is the same between the samples, heat generation during the RCF test is suppressed by the presence of surface nano-crystalline layer formed by the SNW process. In order to estimate the temperature difference between the SRIQ and SNW+SRIQ samples during the RCF test, the SNW+SRIQ sample was subjected to static annealing process at 473, 523, and 583 K for 3.6 $\times$ 10$^3$ s in a vacuum of $< 5 \times 10^{-3}$ Pa, and Vickers hardness was measured, whose results are shown in Fig. 14(b). The hardness values of the SRIQ and SNW+SRIQ samples was almost similar to that of the sample annealed at 523 and 473 K, respectively. From this result, the difference of temperature during the RCF test between the SRIQ and SRIQ+SNW samples can be roughly estimated to be 50 K. Amount of heat generated by friction per unit time $Q$ is given by, $Q = \mu V W$, where $V$ and $W$ show circumferential velocity and weight, respectively. As a $V$ and $W$ was kept constant during the RCF test, it can be seen that smaller $\mu$ in the SNW+SRIQ sample suppress the temperature rise and lead to the longer RCF life.

From the above discussion, it can be concluded that the longer RCF life of the SNW+SRIQ sample was achieved by the combination of the reduction of $\tau_{1 max}$ and the suppression of dynamic softening by reducing generated heat. Recent studies have revealed that densely introduced lattice defects (i.e., grain boundary and dislocation) play important role on the reduction of $\mu$ during the friction test under oil lubrication. As the SNW+SRIQ sample has notable amount of grain boundary on its surface, the hardness of the sample was expected to be reduced by the effect.

### 4.3. Cracks Formed at a Depth of around 850 $\mu$m

Crack was also observed at $z$ of around 850 $\mu$m ($z/a = 2.0$) at the $p_0$ of 3 000 MPa (Fig. 12(e)). The position of the
crack corresponds to the region where the tempered softening occurred during the SRIQ process (see Figs. 7 and 12). From the empirical relation between $HV$ and yield stress $\sigma_y$, the yield shear stress of a material $\tau_y$ can be estimated by $\tau_y = \sigma_y/M = HV/3M$, where $M$ shows Taylor factor. Here, $M$ value of 2.0 was used for the calculation. The $\tau_y$ at the position close to the crack ($z = 900 \mu m$) was estimated to be 560 MPa. The $\tau_y$ at this position under $p_0$ of 3 000 MPa was calculated to be 635 MPa which is close to the $\tau_y$ of the sample (Fig. 15). This can cause a significant development of fatigue at this position and leads to crack formation. Note that this calculation was performed without considering the increase of contact area during the RCF test by wear that this calculation was performed without considering. This can cause a significant development of fatigue at this position and leads to crack formation. Note that this calculation was performed without considering the increase of contact area during the RCF test by wear.

The experimentally observed maximum $\tau_y$ at the position close to the crack ($z = 850 \mu m$) is also affected by the $\mu$ during the RCF test as shown in Fig. 15. The trend is analogous to that at $z = 200 \mu m$; the maximum $\tau_y$ increased with increasing $\mu$. Considering that the SNW+SRIQ sample has lower $\mu$ comparing with the SRIQ sample as was indicated by the friction test and the analysis (see Fig. 6 and section 4.2.), it can be presumable that the RCF life of the SNW+SRIQ was increased by the reduction of the shear stress at the tempered softening region. Shiihara et al. has simulated the RCF test using finite element method and investigated the influence of $\mu$ between the sample and loading-roller on the stress distribution at several depths from the surface. They found that mean stress during the RCF test at each depth, namely, 25, 200, and 1 000 $\mu m$, increases with increasing $\mu$.

Above experimental results clearly show that RCF life under oil lubrication can be improved by the reduction of $\mu$ during the test. More important finding is that the reduction of $\mu$ can be achieved by controlling microstructure of the sample without changing lubricant oil and sample composition. Recent studies have shown that the presence of high-density lattice defects (i.e., grain boundary and dislocation) accelerate the formation of tribofilm from the perspectives of both experiments\textsuperscript{[11,12,18,23,37]} and simulations.\textsuperscript{[15–17]} The findings in this study demonstrated the effectiveness of lattice defects under cylindrical contact condition.

5. Conclusions

In this study, surface nano-crystalline layer was formed by newly developed heavy plastic deformation process called Surface Nanostructured Wearing (SNW), and the effect of the surface nano-crystalline layer on rolling contact fatigue (RCF) was investigated. The obtained results can be summarized as follows:

• By using the SNW process, a surface nano-crystalline layer having high Vickers hardness of approximately 9 GPa was uniformly formed to the depth of around 5 $\mu m$ on a surface of steel sample. The nano-crystalline layer has relatively high thermal stability and retained even after the induction heating and quenching process.

• The traction test revealed that the presence of nano-crystalline layer on the surface reduces friction coefficient $\mu$ under oil-lubricated cylindrical contact condition, which is the same trend with previous ball-on-disk results.\textsuperscript{[11,12,18]}

• The surface nano-crystalline layer formed on the steel sample improved the RCF life of the steel sample; the sample with surface nano-crystalline layer showed at least 4 times longer RCF life comparing with that without the layer. In the sample without the nano-crystalline layer, cracks were formed in subsurface regions with depths of around 200 and 850 $\mu m$, whereas subsurface cracks were not observed in the sample with the nano-crystalline layer.

• The cracks formed at 200 $\mu m$ in depth was close to the position with maximum principal shear stress $\tau_{y\text{max}}$ expected on the basis of Hertzian theory. The analysis considering the effect of $\mu$ suggested that the decrease of $\mu$ reduce the magnitude of subsurface shear stress, leading to the improvement of RCF life.

• After the RCF test, both the sample with and without the nano-crystalline layer showed a dynamic tempering softening during the RCF test owing to a generation of frictional heat during the test. The smaller degree of dynamic tempering softening in the sample with the nano-crystalline layer is presumably worked to suppress crack formation at a depth of around 200 $\mu m$ and is a conceivable origin of the longer RCF life.

• The experimental fact that a subsurface crack at a depth of around 850 $\mu m$ was not formed in the sample with the nano-crystalline layer indicate the variation of stress distribution and reduction of mean stress during the RCF test because of the lower $\mu$.

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