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Surface Integrity and Tribological Properties of Machined Surfaces

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Abstract—The surface integrity of a machined surface is an important factor that dictates several performance characteristics of a metal part. In this paper, the surface integrity aspects are presented specifically with respect to the tribological properties of steel. Test specimens were prepared under varying conditions to induce different levels of surface deformation and hardness. Sliding and rolling experiments were performed to assess the friction and wear characteristics of these specimens using a pin-on-disk type tribotester and a plate-on-ball type set-up. It is reaffirmed that heat treated steels possess superior sliding and rolling fatigue resistance than raw steel. However, for the case of raw steels machined under varying conditions, the harder specimen resulted in higher wear. This result is attributed to the presence of surface cracks that were induced during machining. The results of such findings will aid in the optimization of surface preparation process for tribological applications of steel.

Key words : Surface integrity, Friction, Wear, Machining condition, Deformed layer

1. Introduction

A machine element must satisfy the geometric constraints as well as performance requirements for a given application. The properties of the material selected influence the performance aspect whereas the manufacturing process employed in fabrication of the part dictates its geometrical details. A manufacturing process is deemed to be successful if the dimensions and surface roughness of a part fall within the predetermined tolerance levels. Indeed, in a CIM environment where quality check is performed automatically, the dimensions and the surface roughness of the part are taken as indicators of part quality for a given material. However, it is well known that the surface properties of the workpiece are altered during the fabrication process [1].

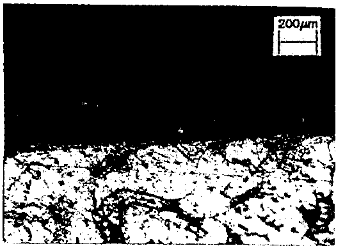
Therefore, for applications where surface properties of the part are important, it is of vital concern that the fabrication process does not degrade the performance of the part even though it may satisfy the geometrical requirements.

Perhaps more than anything else, the tribological characteristics of the part will be most affected by the alteration of the surface properties during fabrication. Though there are numerous literatures available on machining and surface integrity issues, information on the extent to which machining condition ultimately affects the tribological characteristics of the workpiece is difficult to acquire. The primary motivation for this work is to increase the awareness that for sliding or rolling machine elements, the manufacturing process should be optimized with respect to the tribological characteristics in addition to the geometrical concerns.

2. Background

The mechanisms of tribological phenomena such as friction and wear are extremely complicated and depend largely on the nature of interacting system as well as the environment. For example, the primary cause of friction between two solids in contact cannot be described by a single model that is applicable in the general sense. The view that adhesion due to microwelding between asperities of the contacting surface is the major cause of friction in most situations is quite commonly known [2-4]. However, there are numerous research works that emphasize the dominance of mechanical interaction such as plowing in the generation of frictional force [5-7]. It is yet to be clarified which of the two views, quite different in terms of basic concepts, is important with regard to the fundamental cause of friction. It will only then be

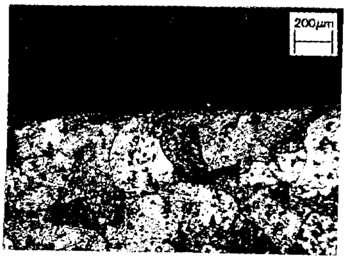
(a) f=0.5mm/rev, v=210m/min, d=1mm



(b) f=0.1mm/rev, v=210m/min, d=1mm

Fig. 1. Effect of feedrate on deformed layer.

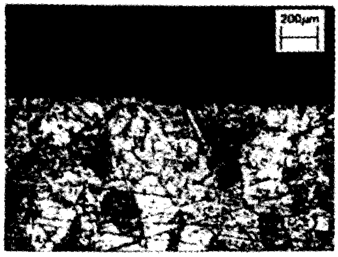
(a) f=0.32mm/rev, v=30m/min, d=1mm



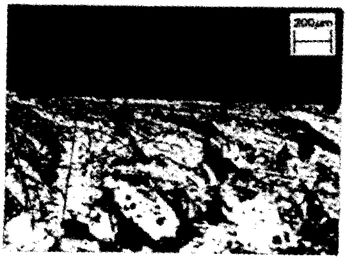
(b) f=0.32mm/rev, v=450m/min, d=1mm

Fig. 2. Effect of cutting speed on deformed layer.

possible to design and fabricate sliding systems with predetermined tribological properties.



(a) f=0.5mm/rev, v=50m/min, d=1mm



(b) f=0.5mm/rev, v=50m/min, d=1mm
tool wear = 0.4

Fig. 3. Effect of tool wear on deformed layer.

Modelling of tribological phenomena is complicated due to the fact that the properties of the solid surfaces are not clearly defined. Not only are the physical properties of the surface different from those of the bulk, but the topographical details are also uncertain at the atomic scale. Furthermore, these properties vary as sliding or rolling takes place over time. Surface topography and roughness effects on friction and wear have been studied extensively over the past [8,9]. Though it is generally accepted that surface roughness does not affect the tribological behavior to any great extent, researchers have found that it does have influence on the tribological behavior in the two extremes of the roughness scale [9,10]. Hardness, on the other hand, is well known to have a direct influence on wear. As Archard's wear law predicts, harder surfaces wear less than softer surfaces in general situations [3,11]. Other properties that define the surface integrity of a surface, such as residual stress, microstructure, and defects, are likely to affect the tribological behavior as well. However, these properties depend much on the conditions in which the surface is subjected to during its preparation process.

The surface properties of a metal part are influenced by the extent of interaction between the tool and the metal surface. Stresses and heat generated during the material removal process alter the physical properties of the surface region [1,12,13]. For example, in the case of machining, a deformed layer forms near the surface region as shown in Figs. 1-3. These samples were prepared by turning steel under various conditions on a lathe. The optical micrographs show the cross sections of machined steel specimen that have been etched to reveal their microstructures.

The feedrate, cutting speed, and tool wear are found to be important parameters in determining the extent of surface layer damage. High feedrate, low cutting speed, and tool wear increase the severity of deformation near the surface. The following sections present the experimental work conducted to investigate the influence of machining conditions and heat treatment on the friction and wear characteristics of steel in dry sliding and rolling contacts.

3. Experimental details

The focus of the experimental work was to evaluate the dependence of tribological properties of steel on the surface preparation process. The effect of machining condition on friction and wear during sliding was investigated using raw steel specimens. Also the wear characteristics of raw steel were compared to those of heat treated steel. Lastly, the tribological properties of raw and heat treated steel specimens for rolling contact were investigated.

3-1. Sliding experiment

Sliding experiments were conducted using a pin-on-disk type apparatus. Steel ball was used as the pin and the test specimen was used as the disk. Normal force of 500 gf and sliding speeds between 0.3-0.5 m/s were selected for the experiments. The total number of revolutions was chosen after conducting pretests to determine the distance to reach steady-state frictional force. Friction was monitored by a force sensor connected to a PC based data acquisition system. Surface properties of the specimens were evaluated using microhardness tester, surface profilometer, optical microscope, and X-ray diffraction. The experiments were conducted in laboratory environment with temperature ranging between 10-20°C and with relative humidity of 30-40%.

3-1-1. Specimen preparation

SM45C steel, which is widely used for machine elements, was used to evaluate the effect of machining condition on the tribological behavior. Specimens in the shape of a disk were prepared on an NC lathe under various machining conditions. The machining conditions were chosen selectively to produce different degrees of surface layer deformation while similar surface roughness is maintained. The primary control factors for machining were cutting speed and the use of cutting fluid. Furthermore, for comparison of wear properties between raw and heat treated steels, SCM420H specimens were used. The chemical compositions and the preparation conditions for the specimens are given in Table 1.

The heat treatment depth for the SCM420H specimen was about 1.3 mm. The hardness and surface roughness for the specimens are given in Table 2. The disks were slid against 6.35 mm diameter STB2 steel ball. The hardness of the ball was HV910 and the surface roughness was Ra 0.15 μm. The chemical composition of the ball is as follows:

Chemical composition of STB2 [14]

Cr	C	Si	Mn	P	S
1.30~1.10	0.95~1.10	0.15~0.35	<0.50	<0.025	<0.025

Table 1. Machining condition and chemical composition of specimen

	SM45C		
	A	B	C
Cutting Speed	300 m/min	300 m/min	2 m/min
Depth of Cut	0.3 mm	0.3 mm	1 mm
Type of Insert	Ceramic	Ceramic	Coated
Coolant	Yes	No	Yes
Chemical Composition[14]	C:0.42~0.45, Si:0.15~0.35 Mn : 0.6~0.9, P~<0.03,S~<0.035		
	SCM420H		
	Raw Material	Heat-treated	
Cutting Speed	250 m/min	250 m/min	
Depth of Cut	0.3 mm	0.3 mm	
Type of Insert	Ceramic	Ceramic	
Coolant	No	No	
Chemical Composition[14]	C : 0.2, Si : 0.23, Mn : 0.72, P : 0.016, S : 0.006, Cu : 0.13, Ni : 0.08, Cr : 1.03, Mo : 0.28		

Table 2. Surface properties

	SM45C		
	A	B	C
Hardness(HV)	240	240	320
Surface Roughness (Ra μm)	0.25	0.27	0.5
	SCM420H		
	Raw Material	Heat-treated	
Hardness(HV)	240	790	
Surface Roughness (Ra μm)	0.35	0.51	

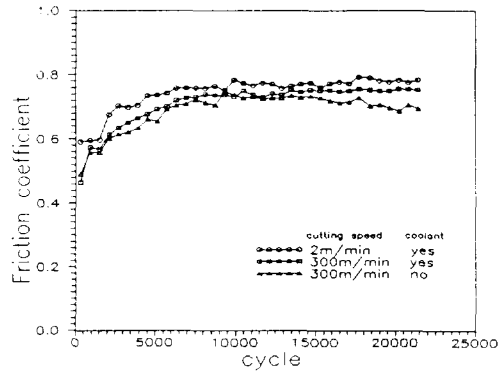


Fig. 4. Friction coefficient respect to number of cycles.

3-1-2. Experimental results

Tribological properties of steel prepared by various machining conditions were evaluated by observing the friction coefficient, microhardness, surface roughness, and surface topography. Fig. 4 shows the friction coefficients for three types of specimens as a function of cycle of revolutions. Each data point represents an average of three experiments. As can be seen from the figure, the friction coefficient rises gradually to a steady state value in about 8000 cycles. The steady state value is between 0.65 and 0.75. Though the friction coefficient for the specimen machined at low speed seems to be slightly higher than the values of the other specimens, the difference is too small to conclude that machining condition affects the frictional behavior.

To evaluate the wear behavior of these specimens, the wear ratios of the specimens can be predicted based on their initial hardness values using the Archard's wear equation [11]. The wear coefficient is taken to be the same in the prediction because the material combination as well as the sliding conditions for the experiments are identical. Then, for a given cycle of revolutions or sliding distance, $V_A/V_B = k_A H_B/k_B H_A$ and $V_B/V_C = k_B H_C/k_C H_B$, where V, k, H represent the wear volume, wear coefficient, and hardness, respectively. Since the wear coefficients are assumed to be same, using the hardness data given in Table 1, V_A/V_B=1 and V_B/V_C = 1.3. Thus, it is predicted that the wear of specimen C should be about 30% less than specimens A or B due to its higher hardness.

Fig. 5 shows the wear profiles of the three specimens. From the profiles of the three experiments

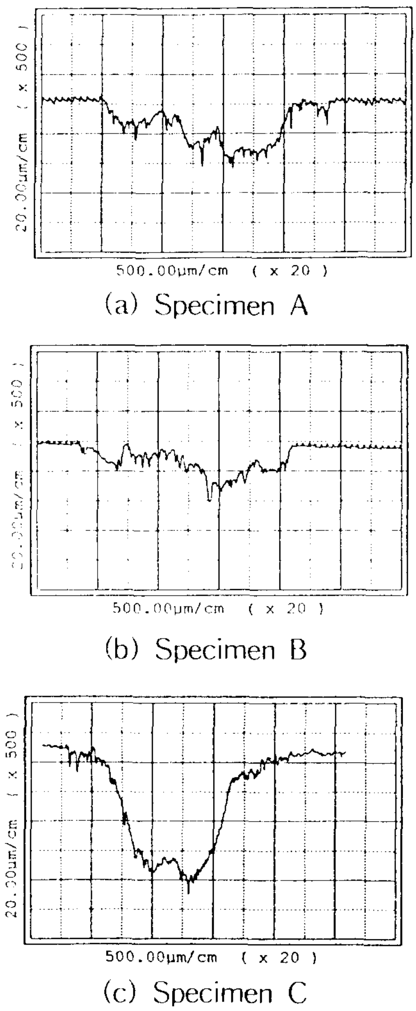


Fig. 5. Wear profile of SM45C specimens.

conducted for each specimen, average wear volumes were obtained to be $V_A = 5.7\ \mathrm{mm}^3$, $V_B = 4.4\ \mathrm{mm}^3$ and $V_C = 7.9\ \mathrm{mm}^3$. Contrary to the prediction, the wear of specimen C was higher than the other two specimens. The discrepancy is probably due to the misleading assumption that the wear coefficients are the same for all three cases.

Based on the experimental data the wear coefficients for the disks and corresponding pins were calculated as given in Fig. 6. The wear volume of the pin was obtained by measuring the weight of the pin before and after sliding. It is shown that the wear coefficient for specimen C, which was machined at low cutting speed, is the highest despite its relatively higher hardness. Attempts were made to explain this behavior from the surface integrity point of view.

As the first measure of surface integrity, the surfaces of the specimens were observed with an optical microscope. Specimen C, which was machined at low speed, had cracks on the surface as shown in Fig. 7. The precise reason for the existence of the cracks is not clear at this point but it is certain that they were introduced as a consequence of the adverse machining condition. Given the existence of surface cracks, it is quite understandable why the wear of the specimen was higher despite having

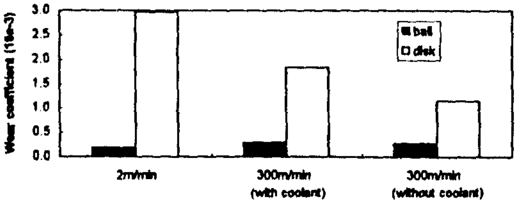


Fig. 6. Wear coefficient of disk and pin.

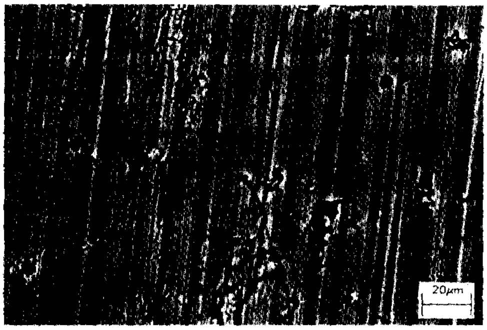


Fig. 7. Micro-cracks on surface at low speed cutting condition.

higher hardness than the other two specimens. It is believed that the pre-existing cracks accelerated the crack propagation process, thus leading to accelerated wear.

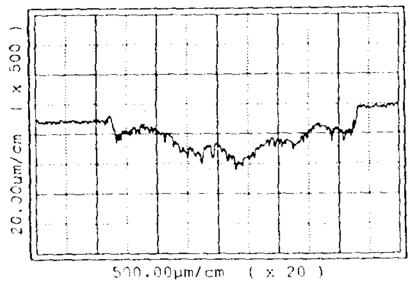
The wear track roughness, hardness, and residual stress for the three specimens are given in Table 3. The surface roughness increased significantly for all three cases due to wear. Specimen C, which experienced the greatest amount of wear, is the roughest. The hardness values of specimens A and B are similar compared to their initial values while the hardness value of specimen C decreased from HV320 to HV220. This may be because the hard damaged layer got worn off during sliding.

The residual stresses for specimens A and B were initially in tension but changed to compression after sliding. On the other hand, the residual stress of specimen C remained about the same in the compressive state before and after sliding. Though further studies are needed to establish a correlation between the machining condition and the residual stress, it seems that sliding action induces compressive residual stress in the surface region. The implication of this finding from the wear point of view is a topic of future research.

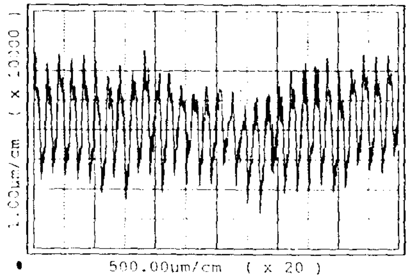
There is no doubt that wear resistance of steel increases significantly after heat treatment. Fig. 8 shows the wear profiles of raw and heat treated SCM420H specimens. The wear scar for the carburized specimen was not discernible, and therefore, wear coefficient could not be obtained. The heat treated specimen only shows sign of slight run-in of the machining mark, thus proving the effectiveness of hardening against wear. However, the wear coefficients of the pins slid against raw and heat treated steels were 3.5×10^{-4} and 9.1×10^{-4}, respectively. This is expected since the pin slid against a harder surface should wear more.

Table 3. Surface properties of wear track after sliding experiment

		SM45C		
		A	B	C
Surface Roughness (Ra μm)		3.54	2.93	7.69
Hardness (HV)		230	240	220
Residual Stress (MPa)	before sliding	90	220	-180
	after sliding	-150	-140	-150



(a) Raw specimen (HV220)



(b) Carburized specimen (HV830)

Fig. 8. Wear profile of SCM420H after sliding.

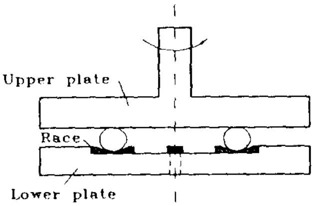


Fig. 9. Plate on ball assembly.

(a) low cutting speed

(b) high cutting speed

Fig. 10. Optical micrographs of SM45C specimens.

The wear resistance of a metal surface depends much on the hardness as Archard's wear equation predicts. However, the integrity of the surface is also an important factor in minimizing wear as presented above. For materials with similar hardness, the presence of surface micro- cracks increases the wear rate significantly. Therefore, surface integrity should be given careful consideration during the part fabrication process from the tribological point of view.

3-2. Rolling experiment

The tribological behavior of steel in dry rolling contact was studied as well. The primary interest of this study was to investigate the effects of machining condition (SM45C) and heat treatment(SCM 420H) of steel on rolling resistance and rolling wear.

3-2-1. Experimental condition

A plate-on-ball type set-up with the capability of monitoring the rolling torque was used for the experiments. The schematic of the plate-ball assembly is given in Fig. 9. The top plate serves as the test specimen and a part from a thrust bearing is used as the bottom race. Due to the curvature of the bottom race, relatively higher contact stress is experienced by the test specimen. A new set of bottom race was used for each rolling test. 16 steel balls were packed around the circumference of the race which eliminated the need for a retainer ring. 48 kgf of normal load was applied on the top plate which amounts to 3 kgf for each ball. Raw (HV240) and heat treated (HV740) SCM420H disks were used for the tests. SCM420H disks were polished to attain a surface roughness of about 0.03 μm. Also, SM45C specimens were prepared to investigate the effect of machining by facing the surface at 164 m/min (HV 240, Ra 0.07 μm) and 2.7 m/min (HV 320, Ra 0.08 μm).

As in the case of the specimens of the sliding experiments, the specimen machined at the low cutting speed had higher hardness and showed evidence of surface microcracks (Fig. 10). 6.35 mm diameter precision ball bearings with surface roughness of 0.02 μm were used.

3-2-2. Experimental results and discussion

Fig. 11 shows the rolling resistance variation as a function of stress cycles, which is equivalent to the product of the number of revolutions and the number of balls between the plates, for steel specimens

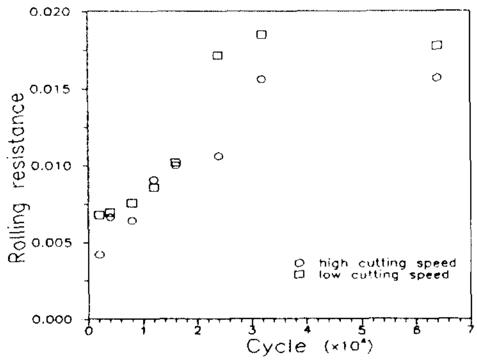
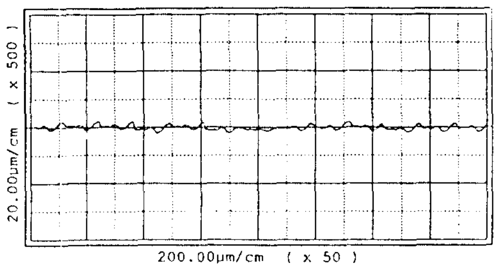


Fig. 11. Rolling resistance of specimens machined at high and low speeds.

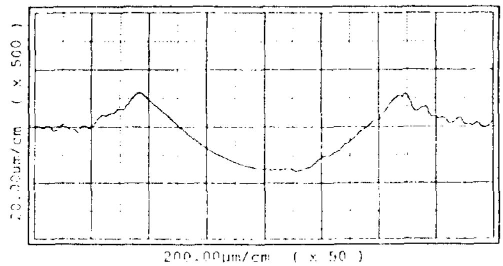
prepared under different cutting speeds. Each point in the figure represents the average of two experimental data. Overall, the initial and steady state rolling resistance for both types of specimens are quite similar.

Fig. 12 shows the profiles of the rolling track after 16 and 4000 stress cycles. As can be seen Fig. 12a and 12b, the surface is slightly deformed after experiencing rolling contact for the first 16 cycles. The deformation of the specimen machined at high speed is significantly larger than the deformation of the specimen machined at low speed. This is probably because of the difference in the hardness of the two specimens. However, the wear profiles of the specimens after 4000 cycles are similar(Fig. 12c and 12d). Fig. 13 shows the optical micrographs of the rolling tracks for the high and low speed machined specimens. As can be seen, the surface morphology of the two specimens are very similar.

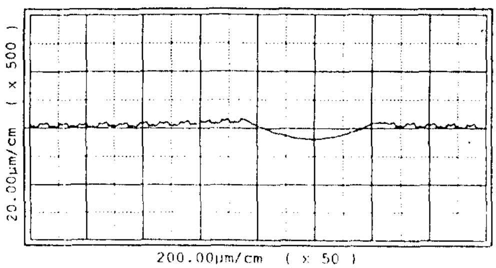
Fig. 14 shows the rolling resistance of raw and heat treated SCM420H steel as a function of number of stress cycles. For the case of raw specimen, the rolling resistance rises to 0.022 within about 2× 10^5 cycles. As for the heat treated specimen, the rolling resistance is less and rises more gradually than



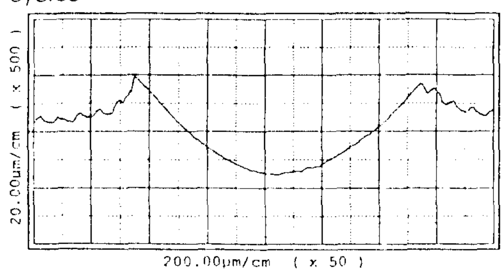
(a) low cutting speed specimen after 16cycle



(c) low cutting speed specimen after 4000 cycles



(b) high cutting speed specimen after 16 cycle



(d) high cutting speed specimen after 4000 cycles

Fig. 12. Profiles of rolling tracks after 16 and 4000 cycles (continued).

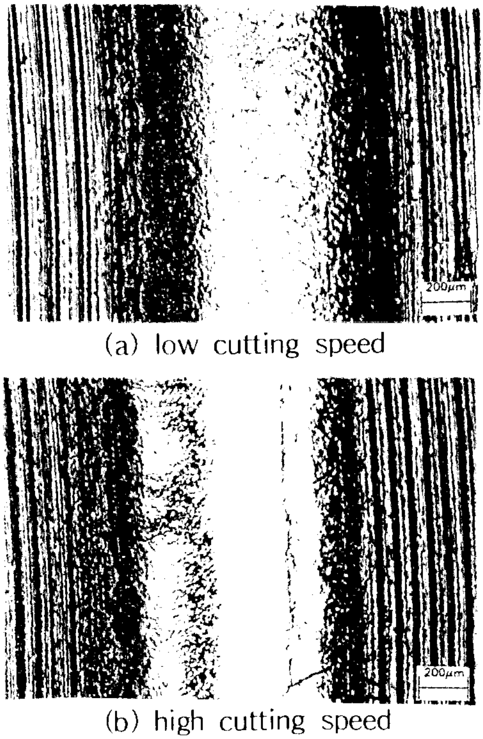


Fig. 13. Optical micrographs of rolling tracks after 4000 cycles.

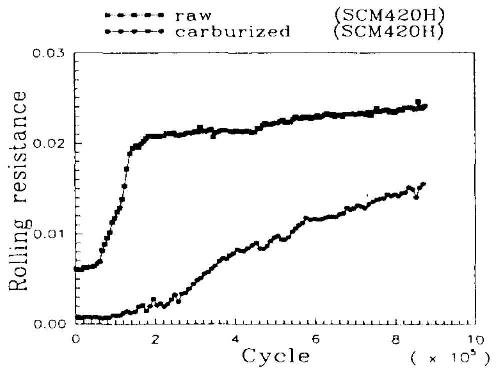


Fig. 14. Rolling resistance of carburized and raw specimens.

the case of the raw specimen. The rise in the rolling resistance is attributed to the increase in surface roughness of the rolling track as wear occurs [15].

Fig. 15 shows the profiles of the rolling tracks after the tests. The wear volumes obtained from the wear profiles were 2.8 mm^3 and 46 mm^3 for heat treated and raw specimens, respectively. These

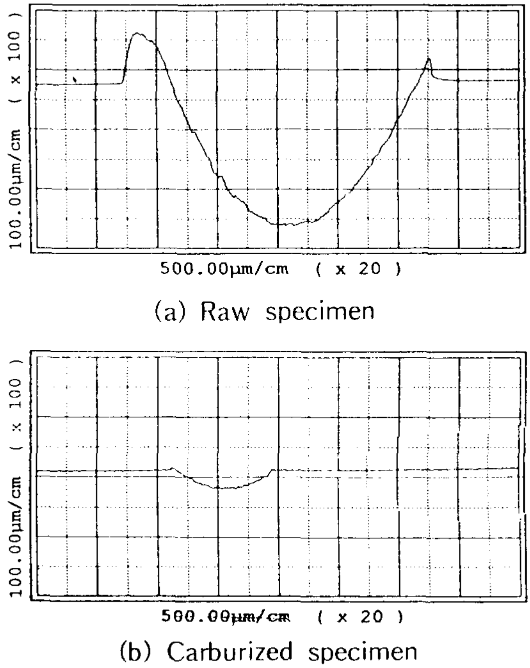


Fig. 15. Profiles of rolling tracks after experiment.

values correspond to wear volume per stress cycle of 3.1×10^{-6} mm^3/cycle and 51×10^{-6} mm^3/cycle for heat treated and raw specimens, respectively.

Overall, the effect of machining condition on the rolling resistance as well as the wear rate does not seem to be significant. Though there is some difference in the deformation amount along the rolling track between the high and low speed machined specimens at the initial stage of rolling, the difference is minimized as the number of stress cycle increases. However, heat treated steel has significantly superior rolling resistance and wear properties compared to raw steel as expected.

4. Conclusions

(1) The friction coefficient values for steel specimens prepared under various machining conditions ranged in between 0.65 and 0.75.

(2) For sliding contact the wear rate of steel machined under severe condition is greater despite higher hardness compared to the steel machined under nominal condition due to the existence of surface cracks.

(3) For rolling contact the rolling resistance as

well as wear bephavior of steel does not seem to be affected significantly by the machining condition.

(4) There is a need to optimize the fabrication process of metal parts with respect to the tribological properties.

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