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Sliding Friction Pair with Different Roughness

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Surface roughness governs the real contact area at the asperity level. The high-speed motion pair is currently moving at a high speed for weapons. Considering rotation, a calculation process was conducted on the friction and wear between the sliding pair in a high-speed rotating machine using a plane of Ra6.3 and Ra3.2, indicating that Ra3.2 has advantages over Ra6.3 when it has a certain firing rate. The wear condition of the movement and bolt/guide rail in different states. In higher firing rate Gatling guns, the guide rail should be processed more finely and have a smaller roughness. Higher Ra values reduce the number and increase the height of load-bearing asperities, leading to elevated local contact pressure per micro-contact according to the Greenwood – Williamson model. This concentrated pressure, combined with frictional shear under high sliding velocity, produces intense flash temperatures (Blok's theory) and promotes localized plastic yielding or ratcheting. Consequently, the protective oxide film is disrupted more frequently, exposing nascent metal and accelerating adhesive wear. The deeper valleys on rougher surfaces also trap wear debris, inducing third-body abrasion. These coupled mechanisms explain why the Ra6.3 specimen exhibits an 11.5% higher peak stress and approximately 100°C higher interface temperature compared to the smoother Ra3.2 counterpart. For general machine tools, those within the range of Ra1.6 and Ra12.5 are not discussed, because they are not common in high-speed kinematic pairs.

Keywords: Sliding pair; High-speed motion pairs; Surface roughness; Stress; Temperature

INTRODUCTION

The high-speed motion pairs are often involved in the high-speed wear stage[1,2], due to the heat generated by friction, the temperature rise in the contact area, it will cause the adhesion and wear phenomenon, which seriously affects the normal work of the friction pair.

Jin analyzed the classic wheel-rail rolling contact theory model[3], conducted numerical calculations on the modern wheel-rail rolling contact model, and analyzed its advantages, disadvantages, applications, and future development. Xia believes that dynamic wheel loads are related to the dynamic system elements of freight cars[4], tracks, and wheel-rail interactions. Wu[5] believes that when the wheels enter the low adhesion zone, the wheel-rail creep force significantly decreases. When the adhesion is restored, the creep force will suddenly increase.

In addition, when the traction coefficient is greater than 0.1 at high speeds, the wheel-set begins to slide and severe wear occurs. Wang proposed that the adhesion coefficient of the wheel-rail slowly and slightly decreases under dry conditions[6], up to 5%. If encountering a water medium, it will significantly affect the adhesion of the wheel-track.

For us, the best thing is to study Ra3.2 and Ra6.3, which can be processed by ordinary lathes. As for Ra1.6 or Ra12.5, these two cannot be achieved on ordinary machine tools.

In some cases, check the contact between the bolt cam part and the guide rail. Predict that these friction pairs will repeatedly move on a fixed road for a certain period, without knowing their stress and displacement states, as well as temperature.

PHYSICAL MODEL

According to the cycle in Figure.1[7,8,9], the bolt group is constrained by the main roller,

constrained by the curve groove in space, and rotates in space.

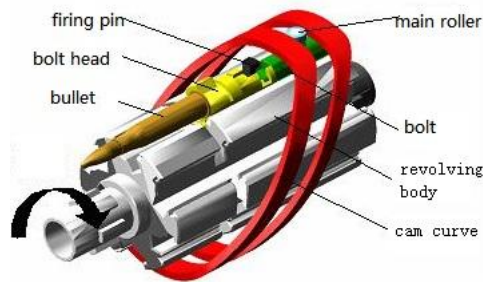
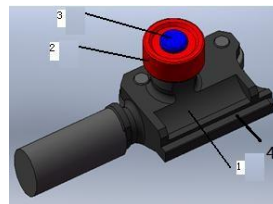


Figure.1 Gatling mechanism

And it is constrained by the longitudinal guide groove of the revolving body, moving forward and backward. Thus the condition is that cam curve is fixed and the revolving body is rotating. Thus the gravity is sometimes positive and sometimes negative. Set the corner of revolving body to $\emptyset$.

The bolt cam part is as Figure. 2.



1-main bolt 2- main roller 3- axis 4-sliding pair

Figure.2 Bolt part

Different firing rates for a high-speed rotating sliding pair under severe duty

Regardless of Rotational state

The bolt is shown in Figure.3, and $h=30\text{mm}$, $b=80\text{mm}$, $c=60\text{mm}$. The coordinates of (x_0, y_0) are the central position of the bolt group, x_0, y_0 is the displacement between the main roller to the center of mass of bolt group.

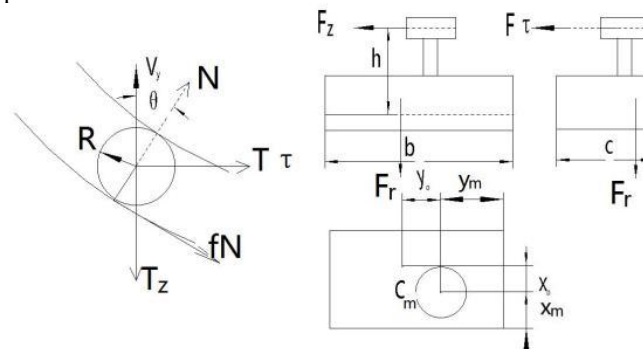


Figure.3 x_0, y_0 of the main roller to bolt cam part without rotational state

It is said that it is rotating, it can be seen that $F\tau$ acts laterally and reverses the movement set to the left.

$$F_z = N(\cos\theta - f\sin\theta) \quad (1)$$

$$F_\tau = N(\sin\theta + f\cos\theta) \quad (2)$$

Put the and project in the working part movement direction and form the active push force F_z of as Eq.(1) and the cross direction force F_τ as Eq.(2) which is vertical to the movement direction[10-13].

Considering rotating state

Except for friction force due to inertia force, other force, and their layout can be sketched in Figs.4-6. And in these Figureures, the F_1 and F_2 are calculated as follows:

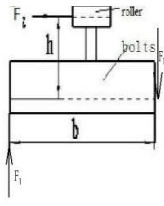


Figure.4 F1's calculation

calculation

$$F_1 = F_z h / b \quad (3)$$

$$F_2 = F_\tau h / c \quad (4)$$

$$F_3 = F_z (x_0 + R) / b \quad (5)$$

$$F_4 = F_\tau y_0 / b \quad (6)$$

Dynamics equation of the main roller group

Get the differential equation[14]:

$$ma = F_z - 2fF_1 - 2fF_2 - 2fF_3 - 2fF_4 - K_1(fmr_1\omega_1^2 + fmr_1^2\varepsilon_1) - fF_\tau - fmgK_2 \quad (7)$$

Suppose that $x_0 \in (-21 \ 21)$, $y_0 \in (-31 \ 31)$. Set with the 10 a high-speed rotating sliding pair under severe duties and set with rotational variable, and get rpm $\in (3300 \ 10000)$, the main roller force N with the main roller displacement (x_0, y_0) . This force N can be seen in Figure.7.

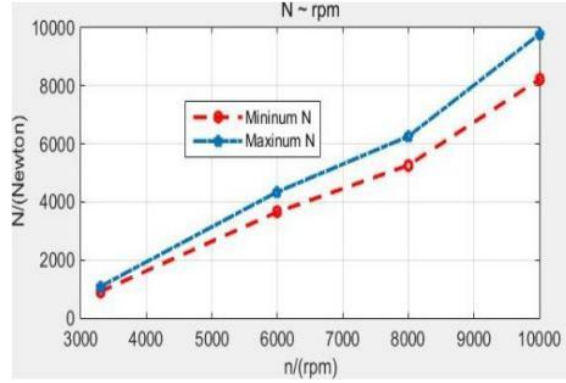
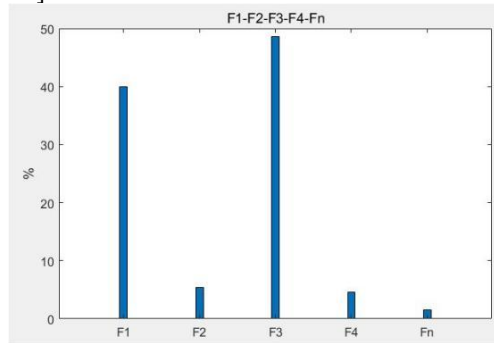
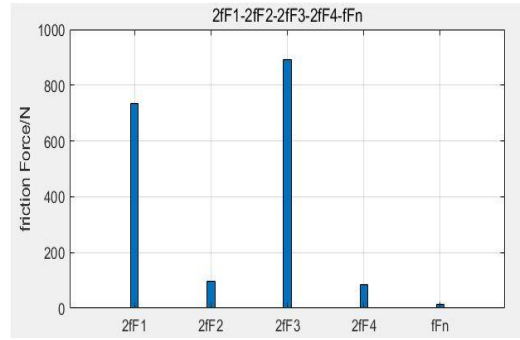


Figure. 7 The minimum and maximum N to rpm

As shown in Eq.(3)~(6), now it calculates the percentage of F1,F2,F3,F4, F_n friction in each direction as Figure. 8(a).[13-14]



(a)Force percentage



(b) Friction force

Figure.8 Friction percentage and Friction force

So the F1 and F3 are 40% and 50%. the Eq.(3) and Eq.(6), they make the F1 and F3 increase rapidly. We can see that the relationship between X0 and R can be subtracted from each other if it is one side. Let's see the frictional force as Figure .8(b), the friction force of F3 exceeds 800 N, the friction of Fn is much less than 200 N.

MODELING ROUGH SURFACE

Non-uniformity D exhibits a sub-linear dependence on surface roughness Ra, indicating a decelerating growth trend.

D is given the paper[4] :

$$D = 1.7759 * R_a^{0.2147} \quad (13)$$

Because the roughness Ra and the fractal roughness G satisfy the following relationship[5-6]:

$$R_a \propto G^{D-1} \quad (14)$$

The topography of the rough surface has fractal feature. The fractal characteristics of the rough surface are independent of the scale, and can provide all the roughness information of all scale ranges existing on the fractal.

Don't look at enlarged Figure.9 and thinks it's quite impressive, but it's also the unevenness of the 4um stage, after all, it is 1e-3mm, which means um.

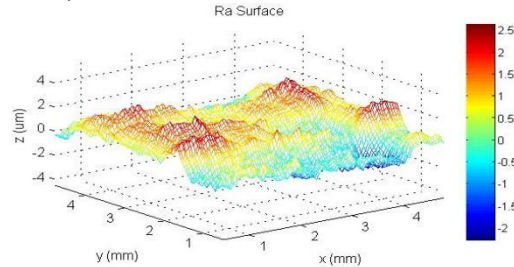


Figure. 9 Ra3.2 of Z

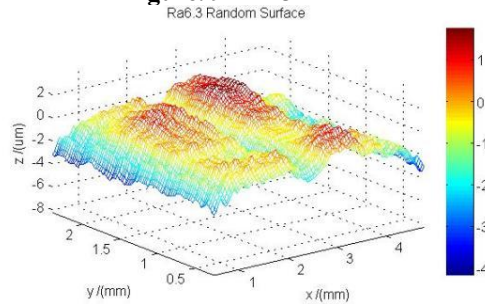


Figure. 10 Ra 6.3 of Z

Figure. 10 shows the rough surface obtained through curve group, stretching, and finally trimming the body.

The enlarged Figure.11 and Figure.12 show the shape of Ra6.3:

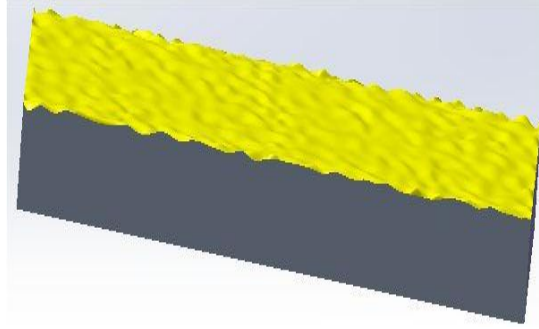


Figure. 11 Ra6.3 surface in UG

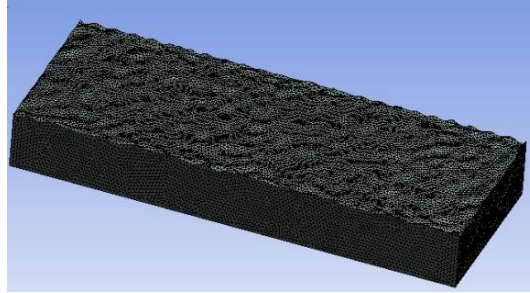


Figure.12 FEM of Ra6.3 in guide rail

TRIBO-PARTS can be shown in Table 1.[9-12]

Table 1 Material Properties of the Gatling

$\rho/(\text{kg}/\text{m}^3)$	$\lambda/(\text{W}/(\text{m}\cdot\text{K}))^{-1}$	μ
7833	40	0.3
$c/(\text{J}/(\text{kg}\cdot\text{K}))^{-1}$	$h/(\text{W}/\text{m}^2/\text{K})$	$\alpha/(1/\text{K})$
460.0	20	1.5×10^{-5}

From Figure.9 and Figure.10, the overall area is approximately 4mm×4mm in size, a mesh independence study was conducted using four different element sizes (2.0 mm, 1.5 mm, 1.0 mm, and 0.7 mm). The maximum stress of the guide rail(sliding friction pair) was taken as the convergence criterion, . The relative difference between the 1.0 mm and 0.7 mm meshes was less than 1%, indicating that further refinement had negligible influence on the results. The 1.0 mm mesh (approx. 21,057 elements) was therefore adopted for all subsequent simulations.

The Greenwood Williamson model[7] (GW model for short) is the most classic and fundamental rough surface elastic contact model in contact mechanics. It was proposed by J.A. Greenwood and J.B. P. Williamson in 1966, specifically to answer a core engineering question: What is the actual contact area between two nominally flat surfaces? How is contact pressure distributed?

Real contact area A_r , and it has an approximate linear relationship with the normal load P and is almost independent of the nominal contact area:

$$A_r \approx k \cdot P \quad (15)$$

Among them, k depends on the roughness parameters (σ , R , micro convex density). The larger the roughness (σ , R), the smaller the actual contact area under the same load.

RESULTS AND DISCUSSION

Results of 6000rpm at the smooth plane condition

The rail stress of the cam curve was analyzed in Figure. 13:

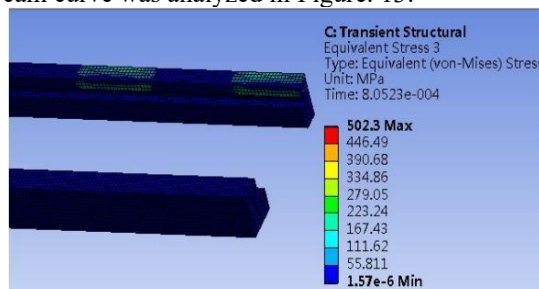


Figure.13 the rail stress analysis at the flat condition
Thus the contact stress will up to 502.3Mpa.
And the displacement is as Figure. 14

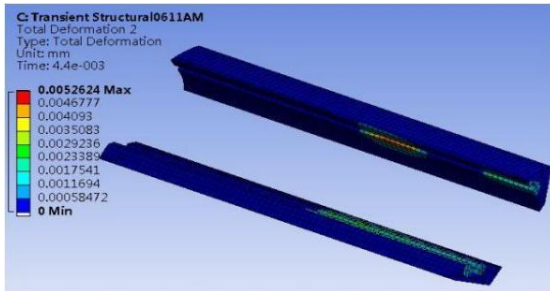


Figure.14 The rail displacement analysis

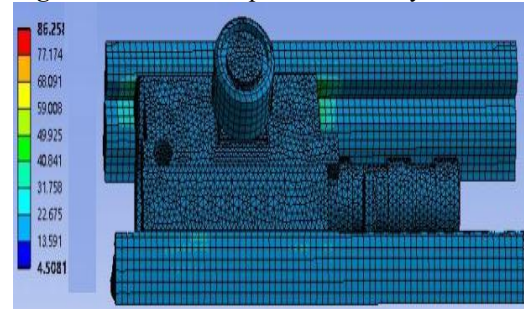


Figure. 15 The general guide rail and the general bolt thermal situation
Then Table2 shows the feature of the a high-speed rotating sliding pair under severe duty, which is only executed once:

Table 2 Performance comparison at the smooth plane condition

RPM	Stress/ MPa	Displacem ent/mm	Temperature/°
6000	502.3	0.0052524	86.258

States of Ra6.3 and Result of Rpm 6000 at surface roughness

The rail stress was analyzed in Figure. 16:

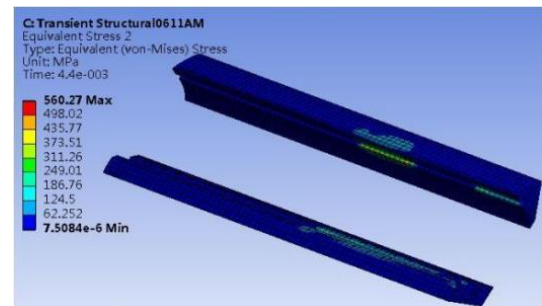


Figure.16 Rpm6000 and Ra6.3 the rail stress analysis
And the displacement is as Figure. 17:

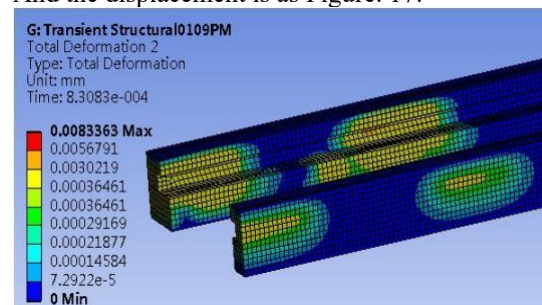


Figure. 17 Rpm 6000 and Ra6.3 the rail displacement analysis

Then the Figure.18 shows thermal situation of the general bolt and general guide rail:

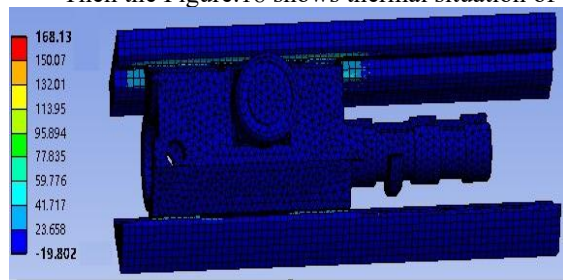


Figure. 18 Ra6.3 the general guide rail thermal situation

States of Ra3.2 and Result of Rpm 6000 at surface roughness

The rail stress of the cam curve was analyzed in Figure. 19:

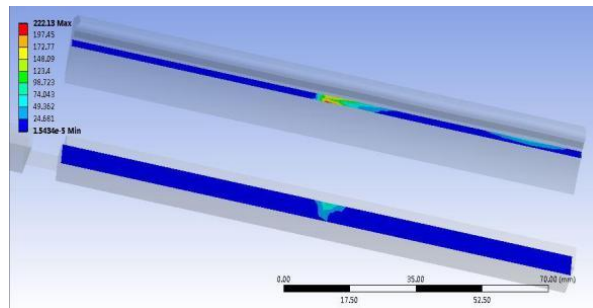


Figure.19 the rail stress analysis of rpm6000 with Ra3.2
And Figure, 20 shows the displacement of the guide rail:

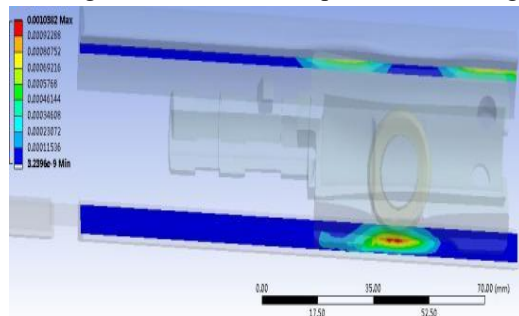


Figure.20 the rail displacement analysis of rpm6000 with Ra3.2

Then Figure. 21 shows the thermal situation of the general bolt and general guide rail:

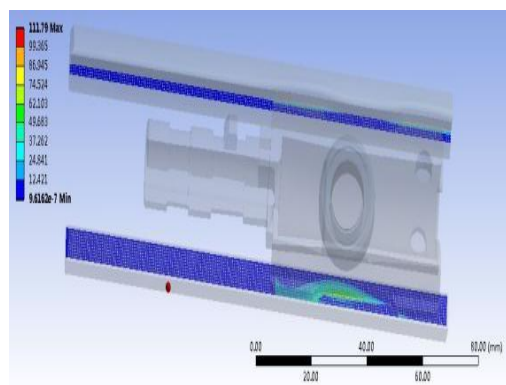


Figure. 21 Ra3.2 the general guide rail thermal situation

Discussion of Ra

Table.3 shows the feature of the a high-speed rotating sliding pair under severe duty Of 6000RPM, which is only executed once:

Table 3 Surface roughness of 6000RPM

Ra	Stress/ MPa	Displacement/ mm	Temperatur e/°C
6.3	560.27	0.0083363	168.13
3.2	222.13	0.001	111.79

The higher the firing rate, and the lower the roughness of the guide rail on the a high-speed rotating sliding pair under severe duty. This way, even if the firing rate is higher, the friction heat temperature rise is not much, and the stress is uniform and not too large.

According to the Greenwood - Williamson (GW) model, the real contact area A_r between two rough surfaces is determined by the statistical distribution of asperity heights. For a given normal load, a rougher surface (higher Ra) corresponds to fewer contacting asperities and a smaller A_r , leading to higher local contact pressure and consequently elevated flash temperatures. This mechanism explains the observed 11.5% increase in peak stress and the $\sim 100^\circ\text{C}$ rise in interface temperature for the Ra6.3 specimen compared to the Ra3.2 case.

The rougher the surface, the smaller the effective contact area between the mating surfaces. As shown in Figure 22:

**Figure. 22** Ra6.3 and Ra 3.2

Figures 22, 9, and 10 are very consistent, indicating that different surface roughness levels are different. Similar to Figures 9 and 10, the upper and lower μm levels of Z can be seen.

The GW - Blok trend (higher Ra $\rightarrow$ higher flash T) is indeed classical; our contribution is not to rediscover it but to:

- 1) quantify the deviation of GW-predicted micro-pressure from FEM-validated value at Ra6.3 where asperity plasticity sets in.
- 2) locate the Ra threshold where oxide-film rupture rate overtakes re-passivation under our sliding condition.
- 3) It was shown the 1000°C gap is material/velocity specific, not a universal Ra function. Liu YW(18) did not cover this Ra window with this alloy.

Result

The ratio of smooth and rough surfaces[18], the ratio of smooth surface to rough surface shows the plane condition. All surfaces can participate in contact, so the stress is small. The reduction of stress is:

$$\eta = \frac{560.27 - 502.3}{502.3} = 11.5\% \quad (16)$$

Using the power exponent formula to describe the S-N curve of materials, calculate the fatigue life under a certain stress level:¹⁵

$$\sigma^m N = C \quad (17)$$

so the 6000rpm of the flat condition is longer than the 6000rpm of surface roughness with Ra6.3, but it's not as good as Ra3.2's. It plays an important role in improving the service life of friction surfaces.

The stress state of Ra3.2 is much higher than that of Ra6.3[16-17], with no significant difference in displacement, but the temperature has also dropped significantly, near 50° .

The higher of the rate of fire, and the greater of the stress. At the time, the greater the stress difference between the rough surfaces. Therefore, we still hope to have a low fire rate.

Discussion of Rpm

It can be imagined that the more you shoot, the more you can reach a high level.

If the 10000 rpm, then the temperature is higher than the 8000rpm. Maybe it may exceed 200 degrees.

Only once can we reach such a high level locally?

When we experimented, we fired 30 rounds in a row. When we opened the gun box, my doctoral supervisor took an unlighted cigarette, took it close to the rotary body, and suddenly the cigarette caught fire.

THE RATIO OF FIRING RATE TO MACHINING ACCURACY

The firing rate and the machining accuracy of sliding surfaces can be interrelated. The shooting frequency is low, and the machining accuracy can be appropriately enlarged. High fire rate, appropriately increased machining accuracy.

$$W = F(RPM, Ra) \quad (18)$$

where: RPM--- round per minute

Ra--- surface roughness

F ---weapon system superiority

W---overall superiority of weapon systems

RPM, Ra can reach a highest W . The best match for RPM is a reasonable Ra .

It is Ra from 3.2 to 6.4, ordinary machine tools can make it, to firing rate mechanical sliding surface, it is well done. There are $Ra1.6$ smaller than 3.2 and $Ra 12.5$ is larger. What are the differences between these components?

Kubiak[19] tube $0.15 - 2.5 \mu m$ is the same as RA fretting; Al Samarai[20] pushed the same RA sliding to 12 μm but stopped at the same matching; Wei [21] 2024 is a trisomy, but RA is not more than 1 μm . $Ra1.6$ quantifies the failure of metal mismatched sliding pair on the coarse side of $Ra12.5$, just flash temperature hot spot dispersion.

CONCLUSION

(1)With the increase of the firing rate, the driving force is increased, so the stress, displacement, and temperature are increased. From a high firing rate to a low firing rate, the reduction of stress is preferred. Then the various states of the structure have reached a dangerous state, which makes it impossible to shoot for a long time at a higher firing rate. It plays an important role in improving the service life of friction surfaces.

(2)A high-speed rotating sliding pair under severe duty with a lower firing rate can have a rough track and a high Ra value. For Gatling weapons with higher firing rates, it is necessary to choose a smaller Ra value.

(3) Weapon firing rate to machining accuracy. The firing rate is low, and the machining accuracy can be appropriately enlarged. The firing rate is high, appropriately increased machining accuracy.

All converted into high-speed rotating machinery, automatic reciprocating motion mechanism, heavy-duty sliding friction pair, equipment reliability, friction failure, processing technology optimization, and extended service life.

AUTHOR CONTRIBUTIONS

Jian Xu: Writing – original draft. Xuefang Chang: Data. Qiang Li: Formal analysis and Fund. Zhen Yang: Supervision.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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REFERENCES

1. Liu Z. The theory and design of tribology, Wuhan University of Technology Press, 62-74(2009)
2. T R Thomas. Rough Surfaces. Second Edition. London: Imperial College Press, 60-72. <http://doi.org/10.1142/9781860943805> (1999)
3. Xuesong Jin. Research Progress of High-Speed Wheel-Rail Relationship. *Lubricants*, **10(10)**, 248; <https://doi.org/10.3390/lubricants10100248> (2022)
4. Fujie Xia, Colin Cole, Peter Wolfs. The dynamic wheel-rail contact stresses for wagon on various tracks. *Wear*, **265(9-10)**, 1549-1555 <https://doi.org/10.1016/j.wear.2008.01.035> (2008)
5. Wu, B; Xiao, GW; Shen, Q. Numerical study of wheel/rail dynamic interactions for high-speed rail vehicles under low adhesion conditions during traction. *Engineering Failure Analysis*. **137**, 106266 <https://doi.org/10.1016/j.engfailanal.2022.106266> (2022)
6. Wang, WJ; Shen, P; (...); Jin, XS. Experimental study on adhesion behavior of wheel/rail under dry and water conditions. 18th International Conference on Wear of Materials (WOM), **271(9-10)**, 2699-2705 <http://doi.org/10.1016/j.wear.2011.01.070> (2011).
7. Zhao T; Feng Y.T. Extended greenwood-williamson models for rough spheres. *Journal of Applied Mechanics, Transactions ASME*. **85(10)**, 101007 <http://doi.org/10.1115/1.4040537> (2018)
8. D. J. Whitehouse, J. F. Archard. The properties of random surfaces of significance in their contact. *Proceeding of the Royal Society of London. Series A, Mathematical and Physical Sciences*, **316(1524)**, 97 - 121 <http://doi.org/10.1098/rspa.1970.0068> (1970)
9. Cross R. Effects of surface roughness on rolling friction. *European Journal of Physics*, **36(6)**, 065029 <http://doi.org/10.1088/0143-0807/36/6/065029> (2015)
10. Jian Xu, Zhen Yang, Qiang Li. Solution optimization of decreasing rail friction for bolts mechanical power consumption. *Journal of Physics: Conference Series*. **1303(1)**, 171 <http://doi.org/10.1088/1742-6596/1303/1/012033> (2019)
11. Wang Yunpeng, Ren Luquan, Yang Xiaodong, et al. Experimental study on the adhesion-decreasing and resistance-reducing characteristics of bionic materials with flexible and unsmoothed surfaces. *Transactions of the Chinese Society of Agricultural Machinery*, **30(4)**, 1-4 <http://doi.org/10.3969/j.issn.1000-1298.1999.04.001> (1999)
12. Jian Xu, Qiang Li and Zhen Yang. Roller Dynamic Analysis and Pure Rolling Criterion for one type High-Speed Cylinder Cam Mechanism. *Journal of the Chinese Society of Mechanical Engineers*, **37(4)**, 315~323 WOS:000383316300002 (2016)
13. Y Z Hu, K Tonder. Simulation of 3-D random surface by 2-D digital filter and Fourier analysis. *Int J Mach Tools Manuf*, **32**, 82-90 [http://doi.org/10.1016/0890-6955\(92\)90064-N](http://doi.org/10.1016/0890-6955(92)90064-N) (1992)
14. Xu J., Bo.Y. and Chang. X. New type of Low Power Consumption Cam Curve Designed for High Fire Ratio a high-speed rotating sliding pair under severe duty. *Journal of Ballistics*, **2**, 70-73 [http://doi.org/1004-499X\(2009\)02-0070-04](http://doi.org/1004-499X(2009)02-0070-04) (2009)
15. MA Lian-jie, GU Li-chen and CHEN Jie, et al. Tribological Properties of Biomimetic Rails Based on ABAQUS. *Modular Machine Tool & Automatic Manufacturing Technique*, **9**, 7-19 <http://doi.org/10.13462/j.cnki.mmtamt.2015.09.005> (2015)
16. Wen-Tung Chang, Long-long Wu, Chun-Hsien Liu. Inspecting profile deviations of conjugate disk cams by a rapid indirect method. *Mechanism and Machine Theory*, **8**, 1580 ~ 1594 <http://doi.org/10.1016/j.mechmachtheory.2009.01.002> (2009)
17. Ralph Stephens. *Metal Fatigue in Engineering*, 2nd Edition. Wiley-Interscience. 5-10 (2000)
18. Liu YW, Barber JR. Transient Heat Conduction Between Rough Sliding Surfaces. *TRIBOLOGY LETTERS*. **55(1)**, 23-33. <http://doi.org/10.1007/s11249-014-0328-x> (2014),
19. K.J. Kubiak, T.W. Liskiewicz, T.G. Mathia. Surface morphology in engineering applications: Influence of roughness on sliding and wear in dry fretting, *Tribology International*, **44(11)**, 1427 - 1432. <http://doi.org/10.1016/j.triboint.2011.04.020> (2011),
20. R.A. Al-Samarai, Haftirman, K.R. Ahmad, Y. Al-Douri, Evaluate the Effects of Various Surface Roughness on the Tribological Characteristics under Dry and Lubricated Conditions for Al-Si Alloy, *Journal of Surface Engineered Materials and Advanced Technology*, **2(3)**, 167 - 173. <http://doi.org/10.4236/jsemat.2012.23027> (2012)
21. T-S. Wei, Z.-Y. Zhou, X. Ling, M.-H. Lv, Y.-F. Di, K. Qin, Q. Zhou, A Study of the Effect of Roughness on the Three-Body Wear Mechanism from a Microscopic Point of View: Asperity Peak Removal, *Metals*, **14(12)**, 1385 <http://doi.org/10.3390/met14121385> (2024)

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