Hardness ratio optimization of HiSi wheel/U71MnG rail tribo-pairs by sliding wear for high-speed train

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Abstract

Hardness matching of wheel and rail steels is important for the economic and safe operation of high-speed trains. A new wheel steel named HiSi has been developed by our group recently. Thus the aim of this paper is to explore the optimal hardness ratio of $H_w/H_r$ for HiSi/U71MnG tribo-pairs. Therefore, HiSi wheel steels with various hardness were prepared by tempering at 500 °C–660 °C. Then microstructure and mechanical properties including hardness, strength, elongation and absorbed energy was evaluated with the comparison of ER8 and U71MnG. With the increase of tempering temperature, cementite morphology was transformed from lamellar cementite to plate cementite then to spheroidized cementite, which improved the ductility and toughness of HiSi steel. Furthermore, the sliding wear test under the hardness ratio of 0.91–1.11 revealed that the optimal $H_w/H_r$ in HiSi/U71MnG tribo-pairs was about 0.98–1.04, which can be attributed to the ploughing damage without material remove, more adhesive films and suitable mechanical properties of HiSi steel tempered at 560°C–620°C.

1. Introduction

Great improvement for China high-speed railways has been achieved over the past decade years and the operating mileage has exceeded 25 000 km by the end of 2017 [1]. The prominent damage of wheel wear induced by long track route, large curve radius and relatively concentrated wheel-rail contact spots seriously reduces its service life. In contrast, the wear damage of rail steels is much milder. In fact, the hardness matching between wheel and rail steels is important for their wear behavior [2, 3]. Classically, wear damage is deemed inverse to the hardness itself according to the Archard’s law [4]. If the rail is harder, wear damage of wheel steel will be severer, which will increase the cost of wheel reprofiling and even may reduce the safe operation. By contrast, if the wheel is harder, wear damage of rail steel will be aggravated, which will increase the costs of rail maintenance and replacement [5]. Therefore, the optimal hardness matching between wheel and rail steels, i.e., $H_w/H_r$ ($H_w$ and $H_r$ are hardness of wheel and rail, respectively) should be explored [1, 6–8].

Many researchers have studied the effect of hardness ratio on the wear behavior of rail and wheel steels. In [9], wheel wear was independent of rail hardness during twin disc test while decreased with the rise of the rail hardness in the full-scale test. The latter phenomenon was also found in [10, 11]. Sato et al [12] conducted twin disc tests keeping wheel hardness constant and changing rail hardness in a range lower than wheel steel. The wheel wear did not change greatly as the rail hardness increased. Markov [13] carried out a pure sliding friction test between wheel and rail rollers with the hardness ratio ranging from 0.375 to 2.667 and the results showed that wear rate of wheel roller was inverse to it hardness and almost independent on the coupled rail hardness.
Razhkovskiy et al. [14] recommended the optimal $H_w/H_r$ to be 0.91–0.97 or close to 1. Zhang et al. [8] performed twin disc test with the hardness ratio ranging from 0.80–1.48 and suggested that $H_w/H_r$ should be 0.95–1.15 to minimize the wear loss of the wheel/rail system while larger than 1.00 to reduce the mass loss of wheel. In summary, various $H_w/H_r$ values were recommended to reduce the wheel wear loss without increasing the rail wear damage.

U71MnG hot-rolled steels are being adopted by China high-speed railway as the speed exceeds 250 km·h$^{-1}$ [15]. Hardness of U71MnG is about 270–280 HB. However, hardness matching of wheel and commercial U71MnG has not been carried out. ER8 wheel steel is widely used in high-speed train and its hardness is about 260 HB. The main drawback of ER8 is large wear loss, which may be resulted from the low hardness ratio of ER8/U71MnG of about 0.93–0.96. Thus a new wheel steel has been developed through composition design and heat treatment optimization [2]. The new wheel steel was named as HiSi for its high Si content. Compared with the ER8 steel, HiSi steel displayed better mechanical properties including hardness of 342 HB, ultra tensile strength (UTS) of 1003 MPa and total elongation of 20.5%. In this paper, to explore the optimal $H_w/H_r$ of HiSi and U71MnG steels, HiSi steel was tempered at various temperatures to obtain different hardness, and then subjected to pin-on-disc wear tests against U71MnG. Subsequently, mass losses of pins and discs were determined and the worn surface was examined. Furthermore, wear mechanism of HiSi/U71MnG steels under pure sliding test was discussed in detail.

2. Materials and experimental procedures

2.1. Materials

Chemical compositions of HiSi, ER8 and U71MnG steels are listed in table 1. Compared to the ER8 steel, ferrite strengthening and interlamellar spacing of pearlite (ISP) refinement were achieved in the HiSi steel by the more addition of Si, Mn, Ni and Cr elements [16–18]. A 40 kg HiSi ingot with the dimension of $130 \times 185 \times 230$ mm$^3$ was fabricated by vacuum induction melting & casting technique. Subsequently, the ingot was forged into rod with a diameter of 80 mm. Then the HiSi steel was machined to cylinders with the dimension of $\Phi 32 \times 75$ mm$^3$ and subjected to heat treatment to obtain various hardness. The detailed heat treatment schedule is shown in figure 1.

Firstly, the HiSi samples were held at 850 °C for 90 min to achieve complete austenization followed by water quenching (WQ) to 525 °C with the cooling rate of about 80 °C·s$^{-1}$ in order to reduce the volume fraction of proeutectoid ferrite and enlarge the undercooling degree of pearlite transformation temperature. Subsequently, the HiSi samples were subjected to spray cooling to room temperature (RT) with the cooling rate of about 8 °C·s$^{-1}$ which can also prevent self-tempering of HiSi specimens. Finally, the HiSi specimens with various hardness were obtained by tempering at 500, 560, 580, 620 and 660 °C for 90 min followed by oil cooling and these HiSi steels were named as HiSi-1, HiSi-2, HiSi-3, HiSi-4 and HiSi-5, respectively.

![Figure 1. Schematic illustration of heat treatment schedule for HiSi steel.](image)

| Steels         | C   | Si  | Mn  | Cr   | Ni   | P    | S    | Fe   |
|---------------|-----|-----|-----|------|------|------|------|------|
| ER8           | 0.57 | 0.36 | 0.76 | 0.19 | 0.11 | 0.010 | 0.004 | Bal. |
| HiSi          | 0.50 | 1.33 | 0.84 | 0.25 | 0.44 | 0.010 | 0.007 | Bal. |
| U71MnG [15]   | 0.65–0.75 | 0.15–0.58 | 0.70–1.20 | ≤0.15 | ≤0.10 | ≤0.025 | ≤0.025 | Bal. |

Table 1. Chemical composition (wt%) of steels used in the present work.

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![Figure 1. Schematic illustration of heat treatment schedule for HiSi steel.](image)

| Steels         | C   | Si  | Mn  | Cr   | Ni   | P    | S    | Fe   |
|---------------|-----|-----|-----|------|------|------|------|------|
| ER8           | 0.57 | 0.36 | 0.76 | 0.19 | 0.11 | 0.010 | 0.004 | Bal. |
| HiSi          | 0.50 | 1.33 | 0.84 | 0.25 | 0.44 | 0.010 | 0.007 | Bal. |
| U71MnG [15]   | 0.65–0.75 | 0.15–0.58 | 0.70–1.20 | ≤0.15 | ≤0.10 | ≤0.025 | ≤0.025 | Bal. |

Table 1. Chemical composition (wt%) of steels used in the present work.
2.2. Sliding wear tests

ER8 wheel steel and U71MnG rail steel were directly cut from commercial wheels and rails, respectively as shown in figures 2(a)–(b) and no additional heat treatment was conducted. The sliding wear test was carried out using a pin-on-disc machine as presented in figures 2(c)–(d). The dimension of the cylinder pin sample is Φ4.8 × 12.7 mm³. The outer diameter, inner diameter and height of the cylindrical ring disc sample are 31.7, 16.0 and 10.0 mm, respectively. The initial surface roughness of pin and disc samples was guaranteed to be about 0.3 μm by accurate grinding.

Sliding wear tests were carried out without lubricant at RT in the atmosphere. Before tests, the pin and disc samples were ultrasonicated in alcohol for 10 min. The sliding wear tests were conducted at 300 rpm, 300 N for 120 min. The rotation speed of 300 rpm of pin is equivalent to the sliding speed of 0.375 m·s⁻¹ which is similar to the sliding speed when the train operation speed is 300 km·h⁻¹ and the slip ratio is 0.45% as a common operation condition. We selected 300 N as a suitable load, so as not to make the pressure too large to affect normal operation of wear test machine and the sample does not produce excessive temperature rise which may interfere with the accuracy of the experiment, but can produce enough measured wear as soon as possible. Weight of the pin and disc samples were measured before and after wear tests using an electronic balance with the resolution of 0.1 mg. In order to guarantee the accuracy of the weight measurement, each wear test was repeated three times.

2.3. Characterization

Original microstructure was observed via a scanning electron microscope (SEM) after ground, polished and eroded by the alcoholic solution containing 4 vol.% nitric acid. Worn surface of pins was examined by SEM and a confocal laser scanning microscope (CLSM). Brinell hardness was determined by a XHB-3000 hardness tester and each sample was measured five times at least. Tensile tests were conducted on specimens with 5 mm nominal diameter using a CMT5105 servo-hydraulic machine at RT with a strain rate of 1 mm·min⁻¹. Charpy impact tests were carried out using a JB-30B testing machine at 20 °C on specimens with cross section of 10 × 10 mm², length of 55 mm and U-notch depth of 5 mm.

![Figure 2. Schematic diagrams of sampling position of (a) pin samples from ER8 wheel, (b) disc samples from U71MnG rail, (c) pin-on-disc wear test configuration and (d) dimensions of pin and disc specimens.](image-url)
3. Results and discussion

3.1. Original microstructure and mechanical properties

Figure 3 shows the SEM images of the HiSi pin samples subjected to various tempering temperature before the sliding wear test. All the microstructure was comprised of pearlite and proeutectoid ferrite. Furthermore, cementite morphology was dependent on the tempering temperature. Three kinds of cementite were observed in figure 3 basing on the length of the lamellae, i.e., lamellar cementite (LC, \( \geq 5 \ \mu m \)), plate cementite (PC, 0.5–5 \( \mu m \)) and spheroidized cementite (SC, \( \leq 0.5 \ \mu m \)). With the increase of tempering temperature, cementite gradually changed from LC to PC then to SC in sequence. The volume friction of different kinds of cementite in HiSi samples was listed in table 2. Cementite spheroidization under high tempering temperature can be attributed to the exacerbated diffusion of carbon atoms.

Cementite morphology influenced the mechanical properties of the HiSi steel as shown in figure 4. With the tempering temperature increasing gradually from 500 °C to 560, 580, 620 and 660 °C respectively, the hardness decreased steadily from 302.2 HB, to 285.0, 273.8, 267.0, 248.8 HB, respectively. And UTS of HiSi steel decreased steadily from 1029.3 MPa to 939.4 MPa and then rapidly dropped to 846.3. According to figures 3(d)–(e) we can see that during this period cementite in large amount transformed from plates into spheroids. As for plasticity and toughness of HiSi, we can see from figure 4(b) that as tempering temperature increased, total elongation remained steady from 500 °C to 560 °C, and then gradually rose to 19.20% at 620 °C and then rapidly jumped to 23.12% at 660 °C. Also this jumping period of elongation is in consistence with cementite in large amount transformed from plates into spheroids. Thus, it can be inferred that the rapid decline of UTS and elongation of HiSi steel from tempered point of 620 °C to 660 °C resulted from a large amount of plate cementite.
transforming into spheroids [19]. The microstructure of HiSi-5 sample tempered at 660 °C was almost entirely spherical cementite, which made the microstructure uniformity better and ensured its high ductility [20]. For impact toughness of HiSi steel, it remained steady from 500 °C to 560 °C, then increased sharply from 24.74 J to 32.87 J and rose slightly to 36.66 J at tempering temperature of 660 °C. The sharp increase of impact toughness was exactly in correspondence to the occurrence of cementite spheroids in figure 3(c). Thus we can infer impact toughness was sensitive to the existence of cementite spheroids [21].

SEM images of the ER8 and U71MnG steels are shown in figure 5. And mechanical properties including hardness, UTS, total elongation and impact energy of ER8 and U71MnG steels are presented in table 3. Most of the cementite in ER8 steel was LC with ISP of 159.3 ± 4.5 nm, slight larger than 131.8 ± 5.7 nm for the HiSi-1 steel with full LC structure too. Moreover, the volume fraction of proeutectoid ferrite was about 11.4% ± 0.7% for ER8 steel and 9.9% ± 1.1% for HiSi-1. HiSi steel exhibited less proeutectoid ferrite can be attributed to the larger undercooling degree. Thus, the hardness and UTS of ER8 steel was only 259.0 ± 5.4 HB and 901.8 ± 18.8 MPa, respectively, much lower than those of HiSi-1, even lower than HiSi-4 with PC and SC rather than LC. Meanwhile, ER8 steel also displayed low elongation of 18.68% and impact energy of 23.66 ± 1.02 J, which can be resulted from the bad deformation ability of LC. Microstructure of the U71MnG steel was full pearlite phase without proeutectoid ferrite due to the high C content. And the ISP in the U71MnG steel was about 248.7 ± 22.0 nm, much larger than that in ER8 and HiSi-1 steels.

Table 2. Volume fraction of different kinds of cementite in HiSi samples.

|       | LC        | PC       | SC        |
|-------|-----------|----------|-----------|
| HiSi-1| About 100%| Little   |           |
| HiSi-2| 60%–80%   | 20%–40%  |           |
| HiSi-3| 40%–60%   | 30%–40%  | 10%–20%   |
| HiSi-4|           | 50%–70%  | 30%–50%   |
| HiSi-5| 20%–40%   | 60%–80%  |           |

Figure 4. Mechanical properties of HiSi steels tempered at different temperatures.
3.2. Wear loss

$H_w/H_r$ for HiSi/U71MnG tribo-pair was 1.11, 1.04, 1.00, 0.98, 0.91 in sequence as tempering temperature of HiSi increased. Mass losses of the HiSi, ER8 pins and the coupled U71MnG discs after the sliding wear tests are shown in figure 6. With the decrease of hardness ratio, the mass losses of the five HiSi steel pins were 122.8, 166.0, 161.3, 166.3 and 216.0 mg, respectively, and the mass loss of the coupled discs were 31.1, 22.4, 24.8, 27.2 and 11.9 mg, respectively. It can be seen that HiSi-1 pin displayed the lowest wear loss while the coupled disc showed the highest wear loss. In contrast, HiSi-5 pin presented the highest mass loss and the coupled disc exhibited the lowest mass loss. It seems to be consistent with the perception that the harder material shows less...
wear loss. But the mass losses were 166.0, 161.3 and 163.3 mg for the HiSi-2, HiSi-3, HiSi-4 and 22.4, 24.8, 27.2 mg for the coupled discs, respectively. The optimization principle of the wear resistance of the wheel-rail system is to reduce the wear loss of the wheel without damaging the rail. Thus the hardness ratio of HiSi-1/U71MnG and HiSi-5/U71MnG were not appropriate due to the high mass losses of the disc and pin. Fortunately, hardness ratios of HiSi-2/U71MnG, HiSi-3/U71MnG and HiSi-4/U71MnG were suitable for the HiSi/U71MnG system to achieve low wear losses of pins and discs simultaneously. Besides, comparison of the wear resistance between HiSi/U71MnG and ER8/U71MnG was evaluated and presented also in figure 6. Compared to the ER8/U71MnG system, HiSi-2, HiSi-3, HiSi-4 pins and the corresponding coupled discs showed lower mass losses. Therefore, better wear performance was achieved in the HiSi/U71MnG system as the hardness ratio of $H_w/H_r$ ranging from 0.98 to 1.04.

3.3. Worn mechanism
SEM and CLSM images of the worn surface from five HiSi pins with different hardness are shown in figures 7 and 8, respectively. For the HiSi-1 pin, abrasive and adhesive damage occurred simultaneously. Considering its high hardness and UTS, micro-cutting is the main abrasive damage. Therefore, shallow abrasive damage was presented in figure 8(a). Besides, a kind of circular peak-shaped adhesion was observed in figure 7(c). This
phenomenon should be attributed to the mechanical difference between HiSi-1 pin and U71MnG disc. The latter one with lower hardness would suffer larger plastic deformation thereby exfoliation of adhesive joints occurred on the disc surface and then left on the pin surface. Compared to the HiSi-1 pin, severer abrasive damage and close adhesive wear were detected in the HiSi-2 pin as shown in figures 7(d)–(f) and 8(b). Moreover, additional adhesive from disc sample was not observed. Thus more mass loss from pin and less wear loss from disc were found in HiSi-2/U71MnG system. In the case of the HiSi-3 and HiSi-4 pins with lower hardness, both abrasive and adhesive damages were aggravated as shown in figures 7(g)–(l). But their mass losses were close to that of HiSi-2 pin as presented in figure 6, which can be mainly attributed to the following reasons. HiSi-3 and HiSi-4 samples showed lower hardness, UTS and larger elongation and absorbed energy as shown in figure 4. Thus abrasive manner was transformed from micro-cutting into ploughing, which just induced plastic deformation rather than material remove. High surface fluctuation induced by ploughing was presented in figures 8(c)–(d). In addition, more adhesive films were generated on the HiSi-3 and HiSi-4 pin surface due to their excellent ductility as shown in figures 7(h)–(l). Furthermore, the adhesive film can inhibit the further wear of matrix. However, with the decrease of pin hardness, the most severe abrasive damage resulted from ploughing was observed in HiSi-5 pin as shown in figure 8(e). Besides, adhesive damage was increased significantly in the

Figure 8. CLSM micrographs of (a) HiSi-1, (b) HiSi-2, (c) HiSi-3, (d) HiSi-4 and (e) HiSi-5 pins after sliding wear tests.
HiSi-5 pin as shown in figures 7(n)–(o). Generally, more adhesive film would be formed in HiSi-5 pin due to its better ductility. However, the adhesive film would be exfoliated because of the low UTS of the matrix. Thus the generation and exfoliation of the adhesive film resulted in the large mass loss of HiSi-5 pin simultaneously.

Figure 9 is the worn surface morphologies of the U71MnG discs coupled with HiSi-1 to HiSi-5, respectively, wherein figure 9(a2) is an enlarged picture of the green framed area of figure 9(a1). It can be seen that grooves caused by abrasive damage occurred on all the U71MnG discs, and grooves on the surface of the disc coupled with HiSi-1 pin were deeper and narrower while wider and shallower as coupled with HiSi-5. The microstructure of HiSi-1 was almost full-lamellar pearlite, which has high strength, high hardness and low coordination deformation ability. Therefore, the wear damage of the coupled disc was severer, and the grooves were narrower and deeper. From the red frame in figure 9(a2) it can be seen that the U71MnG disc coupled with HiSi-1 pin
underwent adhesive wear, caused by shear deformation of the surface material, which is in correspondence to the phenomenon observed in figure 7(c). As for the disc samples coupled with the HiSi-2, HiSi-3 and HiSi-4 pins, similar worn surface morphologies were observed while the grooves were gradually becoming sparse. Since the type of cementite of HiSi-2, HiSi-3 and HiSi-4 - gradually changed from LC to PC and SC, and the LC which is mainly high in hardness and low in coordination deformation ability would cause a large damage to the disc sample. Therefore, as the volume fraction of LC gradually decreases and PC and SC increased, resulting in a gradual decrease in the hardness and strength of HiSi-2, HiSi-3 and HiSi-4 pins and an enhanced coordination deformation ability, - the wear damage to the discs was gradually reduced. However, due to the gradual increase of the plasticity of HiSi pins, hard abrasive debris and cementite particles may be embedded into the soft surface to form a mixed sub-layer [22, 23], thus enhancing the wear resistance to a certain extent, increasing the wear damage of U71MnG disc. Therefore, the wear losses of the coupled U71MnG discs did not change significantly although the hardness of HiSi-2, HiSi-3 and HiSi-4 pins gradually decreased. As for the U71MnG disc coupled with HiSi-5 pin, much mild wear damage was observed because of no LC but only a large amount of SC and some PC formed in HiSi-5 pin, so the grooves on its surface was shallower, wider and more sparse. Moreover, hard abrasive debris and cementite particles which were embedded into the surface of HiSi-5 pin could not be kept and form a mixed sub-layer because of the large plasticity and the low strength of HiSi-5 pin, so that the wear loss of U71MnG coupled with HiSi-5 pin was the lowest.

4. Conclusions

To explore the optimal hardness ratio of \( H_{w}/H_{r} \) for HiSi/U71MnG tribo-pairs, HiSi wheel steels were tempered at various temperatures and then subjected to sliding wear against U71MnG rail steel at RT. Firstly, the original microstructure and mechanical properties of the HiSi, ER8 and U71MnG steels were examined. Subsequently, mass losses of HiSi/U71MnG and HiSi/U71MnG systems were measured and the optimal \( H_{w}/H_{r} \) was recommended. Finally, wear mechanism of HiSi/U71MnG tribo-pairs was discussed in detail basing on the worn surface. And the main conclusions drawn for these results are presented as following:

(1) With the increase of tempering temperature, cementite morphology gradually changed from lamellar cementite to plate cementite then to spheroidized cementite in sequence. And the cementite morphology influenced the mechanical properties of the HiSi steel effectively. Especially, both ductility and toughness of the HiSi steel can be improved by spheroidized cementite.

(2) \( H_{w}/H_{r} \) for HiSi/U71MnG tribo-pair was 1.11, 1.04, 1.00, 0.98, and 0.91 with the increase of tempering temperature. As the decrease of hardness ratio, mass losses of the five HiSi pins were 122.8, 166.0, 161.3, 166.3 and 216.0 mg, respectively, and the mass loss of the coupled discs were 31.1, 22.4, 24.8, 27.2 and 11.9 mg, respectively. Therefore, better wear performance was achieved in the HiSi/U71MnG system as the hardness ratio of \( H_{w}/H_{r} \) ranging from 0.98 to 1.04.

(3) The optimal hardness ratio in HiSi/U71MnG can be attributed to the ploughing damage without material remove, more adhesive films and suitable mechanical properties of the matrix.

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