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## Microstructures and Wear Resistance in Si-Cr Alloyed High-carbon Steel by Low-temperature Isothermal Quenching Process

To cite this article: Jing Yang *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **493** 012064

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# Microstructures and Wear Resistance in Si-Cr Alloyed High-carbon Steel by Low-temperature Isothermal Quenching Process

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**Abstract.** The Si-Cr alloyed high-carbon steel was isothermal processed at 200 °C for 8 h after austenizing at 870 °C and 950 °C, respectively, obtaining low temperature bainitic microstructure, which was composed of lath-like bainitic ferrite and film-like retained austenite. The dry sliding wear resistance was measured under the load of 100 N at a rotation rate of 200 r/min. Worn surface morphologies and microstructures of the isothermal transformed samples were analyzed by means of scanning electron microscopy (SEM), optical microscopy (OM), transmission electron microscopy (TEM) and X-ray diffractometry (XRD). The results show that the wear resistance of the Si-Cr alloyed steel with low-temperature bainitic microstructure is better than that of tempered martensitic microstructure.

## 1. Introduction

Abrasion is one of the serious causes for materials failure, and greatly affects the reliability and lifetime of material leading to enormous economic losses, and therefore, it is quite necessary to study the wear performance. The traditional wear-resistant steel is mainly martensitic and high manganese steels [1-2], which are widely applied in bearings, gears, conveyor chains, wear plates or mining system. Recently, the advanced high strength steels (AHSSs) have been developed. One of them is low-temperature bainitic steel, which can obtain large-size nanostructured products through a single isothermal heat treatment process [3-7]. The isothermal quenching temperature of the low-temperature bainitic microstructure is very low, about one quarter of the absolute melting temperature. At this low temperature, nanostructured bainitic microstructure can be obtained in high carbon and high silicon steel. The excellent mechanical properties is displayed in this nanobainitic steel, i.e., hardness of ~700 HV, tensile strength of 2.3 GPa, ductility in the range of 5 to 30 pct, and toughness of around 30-40 MPa m<sup>1/2</sup> [8-10]. This steel has attracted great interests to the application of wear-resistant parts because of the excellent comprehensive mechanical properties. Recently, a great deal of works have been done on the potential of nanostructured bainitic steel for dry sliding wear [11-16], rolling/sliding wear [17-19], rolling contact fatigue [20] and abrasive wear [21]. They found that the wear resistance of the



nanostructured bainitic sample was better than other samples. However, the wear resistance of the low-temperature bainitic steels has not yet been thoroughly studied.

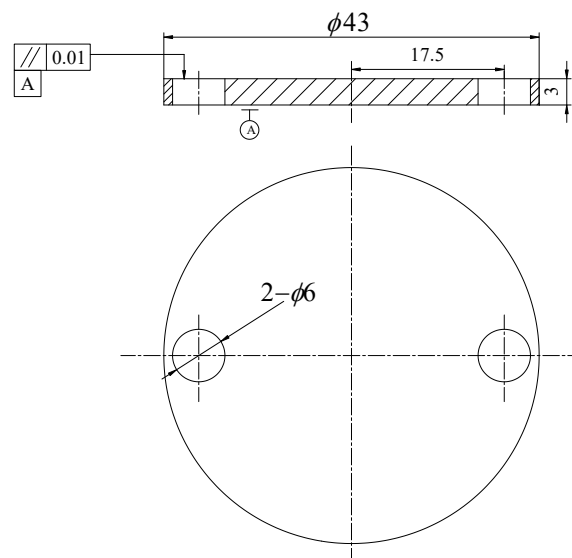
It is the purpose of this work presented in this paper to study on microstructures and wear resistance in low-temperature austempered Si-Cr alloyed high-carbon steel.

## 2. Experimental Procedure

A Si-Cr alloyed high-carbon steel was used for the current research. The chemical composition of this steel is 0.89% C, 1.43% Si, 0.19% Mn, 0.47% Cr, 0.05% V, 0.015% P, 0.0064% S and the balance iron. Phase transformation temperatures were determined by thermilatometry.  $A_{c1}$  is 770 °C,  $A_{cm}$  is 870 °C and  $M_s$  is 170 °C, respectively. The metallographic specimen was machined into 10 mm thickness cylinder bar. The size of the wear testing specimens was shown in Figure 1. The heat treatments of these samples carried out in the study were listed in Table 1. The resulting samples of different heat treatments were designated as 1#, 2# and 3#, respectively. Microstructures of isothermal samples were examined by optical microscopy (OM, Axiover 200MAT, Zeiss), transmission electron microscopy (TEM, H-800, Hitachi) and X-ray diffractometer (XRD, D/max-2500/PC, Rigaku). The OM and XRD samples were mechanically ground, polished and etched using 3% nital. The TEM samples were sliced into ~0.5 mm thickness through wire electrode discharging and mechanically ground down to ~30  $\mu$ m in thickness with SiC abrasive papers. Then the foils were thinned to perforation on a TenuPol-5 twinjet electropolishing device using an electrolyte composed of 10% perchloric acid and 90% glacial acetic acid at ambient temperature and a voltage of 32 V.

**Table 1.** Heat treatment of the steel.

Sample	Heat treatment
1#	Austenitization at 870 °C for 30 min followed by oil quenching and temper at 180 °C for 2h followed by air cooling
2#	Austenitization at 870 °C for 30 min and austempering at 200 °C for 8h followed by air cooling
3#	Austenitization at 950 °C for 30 min and austempering at 200 °C for 8h followed by air cooling



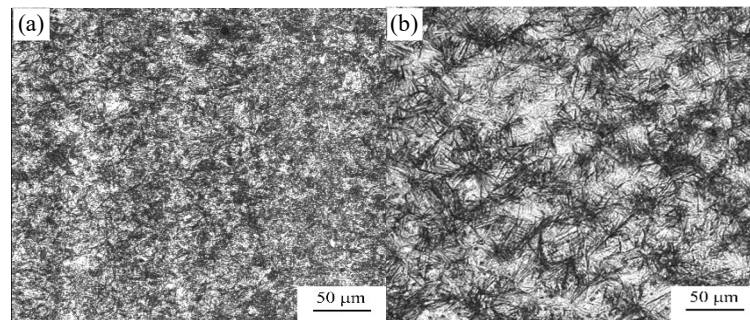
**Figure 1.** Size of the wearing test samples.

Dry sliding wear resistance was measured with a ring-on-disc type wear testing machine (MMU-5G). The tribological pairs tested were GCr15 steel ring sliding against the Si-Cr alloyed steel disc. All the tests were conducted under the following conditions: dry friction, room temperature, 100N load and a 200 r/min rotation rate. The accuracy of measuring the mass of the disc by electronic balance can reach

0.1 mg. The samples need to be cleaned with acetone and ethanol before each test. 1# specimen served as the reference material. The ratio of the wear mass loss of the 1# specimen to the other specimens is used to judge the wear resistance, that is, the relative wear resistance. The worn surface was observed by a KYKY-2800 scanning electron microscopy (SEM) and the wear mechanism was determined.

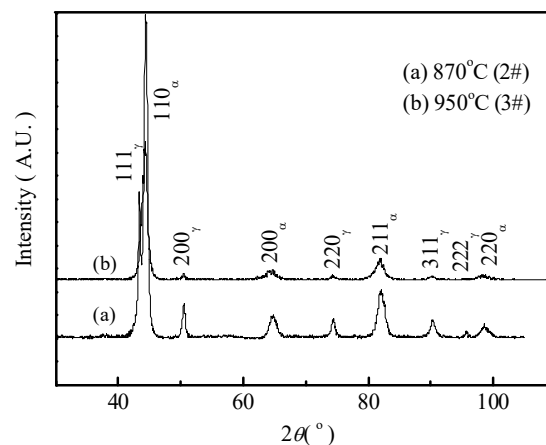
### 3. Results and Discussion

The microstructures of the samples 2# and 3# under the optical microscope are shown in Figure 2 (a and b). It can be seen from the figure that the microstructure of isothermal samples is composed of bainite and retained austenite.

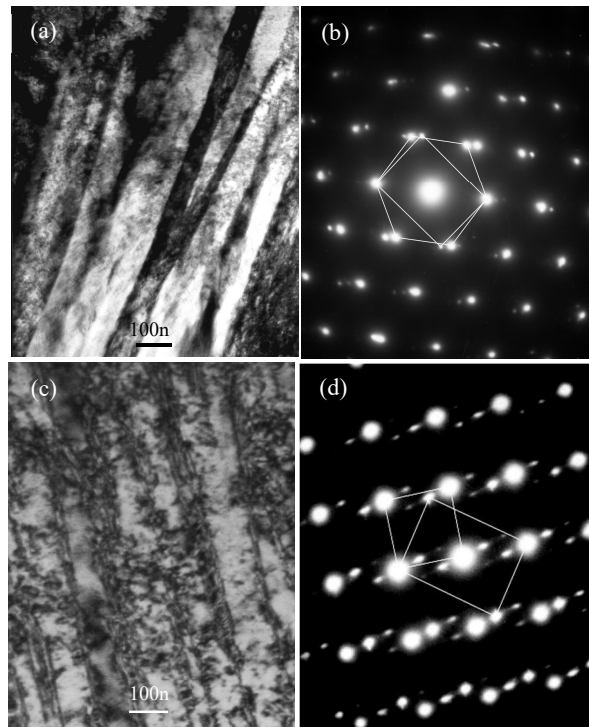


**Figure 2.** OM images of the isothermal samples with austenizing at (a) 870°C (2#) and (b) 950°C (3#).

Figure 3 shows the X-ray diffraction patterns of the two samples 2# and 3#, respectively. It is found that the diffraction peak contains only ferrite ( $\alpha$ ) and retained austenite ( $\gamma$ ) peak, but no cementite peak. X-ray analysis is also used to estimate the content of retained austenite present in the microstructure. By XRD analysis, the amount of retained austenite in specimen 2# and 3# was calculated by the Eq. 3 in literature [22], and the results were about 26.5% and 11.3%, respectively.



**Figure 3.** XRD patterns of the isothermal samples austenizing at (a) 870°C (2#) and (b) 950°C (3#).

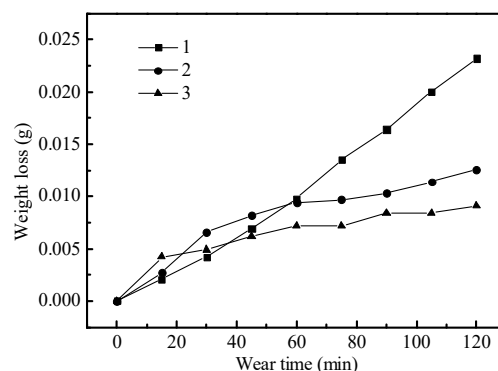


**Figure 4.** Typical TEM micrographs of bainitic microstructure in Si-Cr alloyed steel isothermally treated at 200°C for 8 h after austenizing at different temperatures.

(a) TEM bright-field image of 870°C- austenizing sample, (b) SAED pattern of (a), (c) TEM bright-field image of 950°C- austenizing sample, (d) SAED pattern of (c).

The microstructure and electron diffraction (SAED) patterns of the two isothermal samples were observed by TEM. The observations are shown in figure 4. It can be seen that there are only two phases in the microstructure, lath bainite ferrite and thin film retained austenite. The results of XRD are verified again. The width of lath bainite ferrite is less than 100 nm. Such the microstructure may be referred to as a nanobainitic microstructure.

The weight loss is plotted in figure 5 as a function of wear time of the three samples at 100N load and a 200 r/min rotation rate. It can be seen from figure 5 that the wear rates of the three samples are similar in the initial stage. However, in the later stage, after about 60 minutes, the wear rate of the isothermal specimen decreased obviously, but the QT specimen did not change. Between the two austempered samples, the wear rate is decreased faster for the 950°C- austenizing sample.



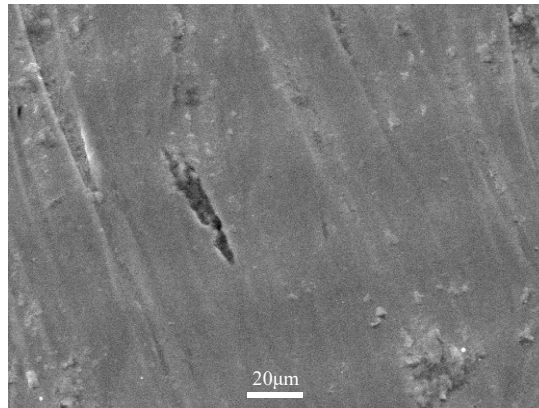
**Figure 5.** The weight loss as a function of wear time at 100 N load and a 200 r/min rotation rate.

**Table 2.** Result of wear testing at 100 N load and a 200 r/min rotation rate.

Sample	Mass before wear (g)	Mass after wear (g)	Mass loss (g)	$\varepsilon = \Delta m_0 / \Delta m$
1#	42.8042	42.7810	0.0232	1.00
2#	43.3666	43.3540	0.0126	1.84
3#	43.0110	43.0019	0.0091	2.55

$\varepsilon$ : relative wear resistance,  $\Delta m_0$ : mass loss of the reference material (1#),  $\Delta m$ : mass loss of 2# and 3#.

The relative wear resistance of the three samples at 100 N load and a 200 r/min rotation rate also reports the same tendency. The data are shown in Table 2.

**Figure 6.** Worn surface of the 2# sample at 100 N load and a 200 r/min rotation rate.

The morphology of worn surface of the 2# sample at 100 N load and a 200 r/min rotation rate is shown in figure 6. It can be seen that there are spalling pits on the worn surface, so the wear mechanism is adhesive wear.

#### 4. Conclusion

In summary, the nanobainitic microstructure is obtained in the Si-Cr alloyed high-carbon steel by isothermal transformation at 200°C for 8h after austenizing at 870°C and 950°C for 30min, respectively. There are only two phases in the microstructure, lath bainite ferrite and thin film retained austenite, of which the retained austenite content is about 26.5 and 11.3%, respectively. The width of the lath bainitic ferrite is less than 100 nm. The 950°C- austenizing sample exhibit a high wear rate. The wear mechanism is adhesive wear.

#### Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 51301033), the Fundamental Research Funds for the Central Universities of Ministry of Education of China (Grant No. N152304001) and the Natural Science Foundation of Hebei Province, China (Grant No. E2017501055).

#### References

- [1] I. El-Mahallawi, R. Abdel-Karim, A. Naguib, Evaluation of effect of chromium on wear performance of high manganese steel, *Mater. Sci. Technol.* 17 (2001) 1385-1390.
- [2] A. Leiro, A. Kankanala, E. Vuorinen, B. Prakash, Tribological behaviour of carbide-free bainitic steel under dry rolling/sliding conditions, *Wear* 273 (2011) 2-8.
- [3] F.G. Caballero, H.K.D.H. Bhadeshia, K.J.A. Mawella, D.G. Jones, P. Brown, Design of novel high strength bainitic steels: Part 1, *Mater. Sci. Technol.* 17 (2001) 512-516.
- [4] F.G. Caballero, H.K.D.H. Bhadeshia, K.J.A. Mawella, D.G. Jones, P. Brown, Design of novel high strength bainitic steels: Part 2, *Mater. Sci. Technol.* 17 (2001) 517-522.

- [5] F.G. Caballero, M.J. Santofimia, C. Capdevila, C. Garcia-Mateo, C. Garcia de Andres, Design of advanced bainitic steels by optimisation of TTT diagrams and  $T_0$  curves, *ISIJ Int.* 46 (2006) 1479-1488.
- [6] C. Garcia-Mateo, F.G. Caballero, H.K.D.H. Bhadeshia, Development of hard bainite, *ISIJ Int.* 43 (2003) 1238-1243.
- [7] C. Garcia-Mateo, F.G. Caballero, H.K.D.H. Bhadeshia, Low temperature bainite, *J. Phys. IV* 112 (2003) 285-288.
- [8] F.G. Caballero, H.K.D.H. Bhadeshia, Very strong bainite, *Curr. Opin. Solid State Mater. Sci.* 8 (2004) 251-257.
- [9] H.K.D.H. Bhadeshia, High performance bainitic steels, *Mater. Sci. Forum* 500–501 (2005) 63-74.
- [10] C. Garcia-Mateo, F.G. Caballero, Ultra-high-strength Bainitic Steels, *ISIJ Int.* 45 (2005) 1736-1740.
- [11] R. Rementeria, M.M. Aranda, C. Garcia-Mateo, F.G. Caballero, Improving wear resistance of steels through nanocrystalline structures obtained by bainitic transformation, *Mater. Sci. Technol.* 32 (2016) 308-312.
- [12] T.S. Wang, J. Yang, C.J. Shang, X.Y. Li, B. Lv, M. Zhang, F.C. Zhang, Sliding friction surface microstructure and wear resistance of 9SiCr steel with low-temperature austempering treatment, *Surf. Coat. Technol.* 202 (2008) 4036-4040.
- [13] J. Yang, T.S. Wang, B. Zhang, F.C. Zhang, Sliding wear resistance and worn surface microstructure of nanostructured bainitic steel, *Wear* s282-s283 (2012) 81-84.
- [14] P. Zhang, F.C. Zhang, Z.G. Yan, T.S. Wang, L.H. Qian, Wear property of low-temperature bainite in the surface layer of a carburized low carbon steel, *Wear* 271 (2011) 697-704.
- [15] R. Rementeria, I. García, M.M. Aranda, F.G. Caballero, Reciprocating-sliding wear behavior of nanostructured and ultra-fine high-silicon bainitic steels, *Wear* 338-339 (2015) 202-209.
- [16] F.C. Zhang, X.Y. Long, J. Kang, D. Cao, B. Lv, Cyclic deformation behaviors of a high strength carbide-free bainitic steel, *Mater. Des.* 94 (2016) 1-8.
- [17] T. Sourmail, F.G. Caballero, C. Garcia-Mateo, V. Smanio, C. Ziegler, M. Kuntz, Evaluation of potential of high Si high C steel nanostructured bainite for wear and fatigue applications, *Mater. Sci. Technol.* 29 (2013) 1166-1173.
- [18] S.D. Bakshi, A. Leiro, B. Prakash, H.K.D.H. Bhadeshia, Dry rolling/sliding wear of nanostructured bainite, *Wear* 316 (2014) 70-78.
- [19] A. Leiro, E. Vuorinen, K.G. Sundin, B. Prakash, T. Sourmail, V. Smanio, Wear of nano-structured carbide-free bainitic steels under dry rolling-sliding conditions, *Wear* 298-299 (2013) 42-47.
- [20] W. Solano-Alvarez, E.J. Pickering, H.K.D.H. Bhadeshia, Degradation of nanostructured bainitic steel under rolling contact fatigue, *Mater. Sci. Eng. A* 617 (2014) 156-164.
- [21] S.D. Bakshi, P.H. Shipway, H.K.D.H. Bhadeshia, Three body abrasive wear of fine pearlite, nanostructured bainite and martensite, *Wear* 308 (2013) 46-53.
- [22] A.K. De, D.C. Murdock, M.C. Mataya, J.G. Speer, D.K. Matlock, Quantitative measurement of deformation-induced martensite in 304 stainless steel by X-ray diffraction, *Scr. Mater.* 50 (2004) 1445-1449.