Deep Analysis of Free-cutting Phase and Its Distribution in Japanese SF20T Pen Tip Steel

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Abstract. This paper aims at investigating the existence state of free-cutting phase in Japan SF20T free-cutting stainless steel (one of the most widely used pen tip steel). By using the devices of an optical microscope (OM), a scanning electron microscope (SEM), electrolytic etching, and Vickers hardness meter, the quantity, composition, shape, size, distribution of the free-cutting phase in the steel and the change of hardness of steel were analysed and characterized, strive to find out the reason of the performance of SF20T steel is far superior to that of other countries' pen tip steel. The results show that the morphologies of inclusions in the steel were mostly in spindle shape, and their distributions were dispersed and quite uniform. The free-cutting phases, MnS in spindle, Pb, and MnTe, were beneficial to enhancing the cutting performance of the steel. In contrast to domestic materials, the distribution of inclusions in the Japanese steel was more uniform, thereby providing key significance for production of pen-making and steelmaking in domestic plants.

Keywords: pen tip steel; free-cutting phase; morphology; hardness.

1. Introduction

As the "crown" of manufacturing industry for production of the pen tip steel, the ballpoint pen steel in recent years has been widely concerned. In early 2016, China Premier Li Ke-qiang even issued a sigh of difficult ball-making of the pen for pen-making industries. More than 3000 enterprises annually produce more than 40 billion ballpoint pens, nearly occupying 80% of the global market share. But the materials of pen tip (pen holder)-super free-cutting stainless steel are totally derived from the imports all the time. In 2017, Tai-steel Group[1], a Chinese enterprise, first announced a successful research and developed the pen tip steel. But the actual effect was not satisfactory due to poor machinability and great costs. Therefore, full scales of mastering the advanced technologies for the production of pen tip steel are of great importance for Chinese steelmaking plants.

In the early days, the materials for pen tip steel were lead-containing brass and nickel-white copper. Due to the poor corrosion resistance, both materials were replaced by free-cutting stainless steel as the most widely used material for ballpoint pen tip steel[2]. At present, most of it is ferritic stainless steel. The hardness of ferrite is low and its plasticity is good. So the ferritic stainless steel is easy to deform and produces a sticky knife phenomenon during cutting, affecting the cutting performance of steel. The usual solution to improve the cutting performance of the material is to add the free-cutting elements to steel, with easier cutting of ferrite stainless steel[3].

From many studies on pen tip steels, it can be found that the distribution, size and shape of free-cutting phases of domestic pen-point steels are significantly different from those of foreign high-end pen tip steels, which results in great differences in steel properties. Nowadays, because of excellent properties, the Japanese pen tip steel has still been dominating the worldwide pen-making industries, occupying the
first place. Thus, this paper analysed the best SF20T pen tip steel of Japan currently to detect the free-cutting phase and its distribution. Most importantly, it provides a comprehensive understanding of the production of Japanese pen tip steel for development of new materials, and gives more useful references for domestic related pen-making and steel enterprises.

2. Analysis of Steel Composition
The SF20T steel is an S-Pb-Te ferritic free-cutting stainless steel, and its chemical composition was obtained in this study by an inductively coupled plasma spectrometer determination and carbon sulfur analysis. The chemical composition of steel is shown in Table 1. The carbon content of SF20T ballpoint tip steel was 0.010%, which was a ferrite stainless steel. The sulfur content was 0.290%, classified into high sulfur steel. The Mn content was 1.070%, and the Mn/S was over 3.5 to form a large number of MnS, an easy-cutting phase.

By generating stress concentration at the cutting contact, the cutting performance of steel is improved due to the production of melting brittle and lubrication effects. The Te content was 0.028% and was easy to form MnTe, attached to the outer surface of MnS to prevent its deformation. MnTe plays a role in controlling the form of MnS, thereby further improving the cutting performance of steel[4].

| Table 1. The chemical composition of pen tip steels (wt. %) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C               | Si              | Mn              | Cr              | Mo              | S               | Pb              | Te              |
| 0.010           | 0.330           | 1.070           | 19.650          | 1.780           | 0.290           | 0.180           | 0.028           |

3. Analysis of Free-cutting Phases

3.1. Methodology
Firstly, two detection planes of metallographic samples from the rolled rod were that one was parallel to the rolled direction (longitudinal direction) and the other was perpendicular to the rolled direction (transverse direction). The shape and distribution of inclusions were observed with the OM after polishing. The statistics for each sample with 20 photos×100 magnification were carried out with Image-Pro Plus software to quantitatively count the number, size, and distribution of the inclusions. The non-aqueous solution was used to observe the three-dimensional morphologies of the inclusions. The electrolyte solution consists of 1% ammonium tetramethyl chloride-10% triethanolamine-methanol, located in a low temperature thermostatic tank to maintain the electrolysis temperature of the sample in the experiment steady. The electrolytic parameters were that electricity density of 0.2 A, time~25 min. The two-dimensional and three-dimensional morphologies of the inclusions in polished and electrolytic samples were observed using the OM and SEM with spectrum analyser. The inclusion composition was detected to explore the free-cutting phases in the tip steel. Also, the Vickers hardness meter was used to test the hardness of the steel matrix and inclusions.

3.2. OM Analysis
The horizontal and vertical polished planes of the samples were observed by OM. Fig. 1 shows the morphology and distribution of inclusions under×200 viewing field. A large number of inclusions were observed. Fig. 1(a) shows that majority of inclusions were in round or oval shape and distributed uniformly with sizes of 10 μm. Fig. 1(b) shows that most of inclusions were in oval shape in the longitudinal direction, illustrating that the inclusions in SF20T steel were in spherical or spindle-shaped. In order to analyse the variation of the inclusion size along the rolling direction, a result of the finished pen tip in the previous study by our team was chosen for comparison with SF20T steel, as shown in Fig. 1(c). Compared to the transverse direction, was significantly reduced to 5~8 μm. And after the drawing of the steel, the inclusions were in fractures, and their sizes were also significantly reduced by 3~6 μm. Thus, the size of the inclusion was reduced to avoid the formation of continuous long-bar inclusions caused by the anisotropy of steel.
According to the statistics for the inclusions, the total number of inclusions was 3199 at viewing field area of 5814600 μm², and the density of inclusion was 550/mm². The average area of an inclusion was 34.8 μm² with an equivalent diameter of 4.87 μm. Fig. 2 shows detailed statistical results of the inclusion equivalent diameter and aspect ratio. Fig. 2(a) shows that the distribution state of inclusion equivalent diameter was that 1–2.5 μm occupied 39.95%, the 2.5–5μm occupied 19.19%, and > 5 μm occupied about 40%. Fig. 2(b) shows that the aspect ratio of 1–3 occupied 83.964%. Combined with the inclusion pattern in Fig. 1, it is confirmed that most of the inclusions in the steel are spindle-shaped, spherical and spheroidal, and 15.067% of the inclusions had a aspect ratio of 3–6, and few inclusions showed a aspect ratio of more than 15, accounting for only 0.96% of the total. Most inclusions in steel were spherical or spindle-shaped, and the average aspect ratio of the inclusions was 2–3. Usually the smaller the length and width value of the inclusion in steel is, closer to the ball, the more favorable the cutting performance of the steel. The small length and width of the inclusions in steel can relatively avoid the anisotropy caused by softness phases in the cutting process. The breaking chips are usually in short and small curls to ensure that the steel has a good cutting performance[5].

3.3. Analysis of Inclusion Composition

The use of energy spectrum was adopted for further observation of the inclusions. The point 2 in Fig. 3(a) shows that the composition of light grey inclusions was a free-cutting phase, MnS. Because of a good plasticity, MnS in the rolling process is easily elongated and sticky with the tool, so it is usually in long strip, with a strip or curling chip, and not easy to be segregated, with poor surface finish. The point 2 in Fig. 3(b) shows that MnS inclusions in SF20T steel were in spheroid shape. At same time, the chip was in C-type, and the debris was easy to be segregated and to improve the finish of the steel surface in the cutting process. Meanwhile, the white bright color area of point 4(a) after detection was MnTe, MnTe-MnS. Both MnTe and MnTe-MnS tended to be in spherical or spheroidal shape, playing key roles in controlling the form, beneficial to improving the cutting of steel. In addition, MnTe is also an important free-cutting phase, which plays the role of stress concentration source, lubrication, etc. during cutting[7]. The compositions of point 1 in Fig. 3(a)-(c) were detected a certain amount of lead. Pb is difficult to be dissolved into iron matrix. Pb is rarely combined with alloy and non-metallic elements to
form compounds, often attached to ends of MnS, or iron matrix in a free state, thus forming a morphological distribution in Fig. 3. In the process of cutting, strong friction between cutting tools and chips, so the lead particles are melted, resulting in lubrication effect, beneficial to chip-breaking and brittle effect, further improving the cutting performance of steel and tool life\cite{8-10}.

Figure 3. Schematics of two dimensional SEM morphologies

3.4. Analysis of 3D Morphology

After the electrolysis etching of the sample with non-aqueous solution, steel matrix was dissolved; whereas the inclusions inlayed in the steel were not dissolved exposed to the surface of the steel in a three-dimensional form. The tri-dimensional morphologies of inclusions were observed by SEM, which were divided into three types according to the form categories of sulphide\cite{11}: I-type, which is mainly spheroidal, spherical. The transverse and longitudinal tri-dimensional morphologies in inclusions were respectively shown in Fig. 4(a) and (b). As evident in the figure, the MnS in SF20T tip steel is a typical Class I and III inclusions.

Further analysis of the inclusions using the OM, is shown in Fig. 4(c). The inclusions were mainly free-cutting phase MnS, and there was a small amount of white bright Pb (point 3) at ends. Attached to the package, the spherical inclusions are not easy to deform during the rolling. Presence of free-cutting phases can effectively improve the cutting performance of steel.

Figure 4. Tri-dimensional morphologies of inclusions after etching

3.5. Micro-hardness Analysis of Steel and Inclusions

The micro-hardness values of the steel and inclusion were detected, with 10 points for steel and 21 points for inclusions. A load of 10 kgf and a loading and unloading time of 5 s were performed. The hardness in Fig. 5 shows that the hardness of steel matrix was larger, and varied little with the average value of 269.9 kgf/mm². In contrast, the micro-hardness of the inclusions was relevantly smaller, with an average of 109.0 kgf/mm². The hardness of the inclusion was more unstable, and a small number of the points owned larger hardness values but far less than steel.
In general, the hardness of steel was in 170.0~230.0 kgf/mm$^2$ and had enough embrittlement\textsuperscript{[12]}, with better processing performance. The great hardness harms the knife life, and accelerates the tool wear. However, the smaller hardness causes the sticky knife, deteriorating the process under the cutting force. All of the cutting performance has a negative impact.

4. Conclusions
(1) The inclusions in SF20T tip steel are mostly in spindle and spheroid shape (Class I, Class III). The equivalent diameter of inclusions in the cross-section was about 2.5, and the average aspect ratio was 2~3, with the uniform and dispersed distribution in steel.
(2) The free-cutting phases in steel were MnS, MnTe, Pb; where MnS was in light gray, spheroidal. MnTe and part of Pb in white color mainly wrapped the MnS.
(3) The micro-hardness value of steel matrix in pen tip steel was 269.9 kgf/mm$^2$; while the hardness of the inclusions was in range of 42.3~179.8 kgf/mm$^2$, with average value of 109.0 kgf/mm$^2$, beneficial to reducing the cutting force of the steel.

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References
[1] Wang F, Hu L N and Huang C B 2017 Tens of billions of pens will be equipped by Chinese tip Pioneers p 42-43
[2] Li G Z, Hui R and Li J H 2002 Development of 30MnVS for free cutting and quenching and tempering steel for passenger cars Iron & Steel p 42-45
[3] Feng M Y, Yan W B and Zhang Y M 2014 Quality analysis and improvement of X1215 free cutting steel Hebei Metallurgy p 46-48
[4] Wang Y J 2016 Numerical investigation of processing properties of pen tip drilling free-cutting stainless steel Xi’an University of Architecture and Technology
[5] Ma Y J, Li L L, Xin W and Li J S 2018 Study on micro-inclusions behavior of 1215 free-cutting steel Value Engineering p 207-208
[6] Watson J D 1986 Microscopy and the development of free-machining steels. Applied Metallography Springer Boston MA
[7] Shen P, Yang Q K and Zhang D 2018 Application of tellurium in free-cutting steels Journal of Iron and Steel Research, International p 787-795
[8] Luo G and Wang H M 2015 Analysis of microstructure and property of a free-cutting stainless steel Shanghai Metals p 10-14
[9] Mao Z Q 2002 Development of domestic and overseas free-cutting steels Automobile Technology & Material p 1-4
[10] Liu H L 1998 *The function mechanism of MnS in YF45V steel* Machinery Development p 25-27
[11] Sims C E and Dahle F B 1938 *Effects of various deoxiders on the structure of sulfide inclusions* Transactions Amwerican Foundry Society p 65
[12] Information on https://zhidao.baidu.com/question/262644469790890045.html