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Review

En-Garde! A Review of Fencing Blade Material Development

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Abstract: Using two fencing swords manufactured in Europe and China, we investigated the typical materials used for fencing blades and compared the experimental results with the nominal compositions of a variety of steels. We found that spring steels and maraging steels were the primary metals used in fencing blades. The review then provides an overview of the chemical compositions, heat treatment processes, microstructures and associated mechanical properties of these materials. By combining the requirements for the safety of athletes, mechanical behaviors of different steels, and production costs for industry, we introduced possible directions for the heat treatments and processing methods that have the potential to enhance performance and overcome the limitations of previous materials. In addition, an ultra-strong steel, Fe-9.95Mn-0.44C-1.87Al-0.67V which could be a promising new candidate in this area, was recommended. Finally, we suggested that successful cooperation between manufacturers and researchers is necessary to reach the various requirements of fencing blades to meet the growing popularity of fencing in China.

Keywords: fencing blades; spring steels; maraging steels

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1. Introduction

A sword is a traditional weapon that has been used across cultures for thousands of years. It has been used for hunting, defending against wild animals and even during face-to-face fighting in battle [1–8]. Traditional swordplay and rules gradually developed into modern fencing in the late 19th century and it became one of the earliest Olympic sports [9,10]. As a sport, fencing keeps evolving, not only developing the game rules and types of competition, but also the material used to make blades and the electronic armor that can automatically record "touches" [11]. A sword with a high-performance blade can assist fencers to play to their strengths and skills, and ultimately score points. For example, the modern speedy response and excellent flexibility of blades help fencers with their hand-feeling and contribute to fluent movement during combat [12,13].

However, in a fencing match, blades are often touched, hit, hacked and even bent. This greatly fluctuating stress can generate cracks, which will propagate incrementally with each stress cycle and may lead to unexpected blade fatigue failure [14]. These fractures involve the replacement of blades and even have the potential to cause severe injuries to fencers [15]. To practice this sport under safe conditions, the material used to make fencing blades has to display excellent strength, toughness and fatigue resistance [12,16,17]. It is generally considered that the fatigue limit is positively correlated to strength, whereas the fatigue threshold is inversely related [18]. Therefore, when selecting blade material to

optimize blade strength and fatigue resistance, it is also important to pay attention to its ability to resist initiating cracks.

Although the international fencing authority (Fédération Internationale d'Escrime, FIE) prescribes strict standards regarding geometrical constraints, material properties, and blade mechanical behavior, there is little research directly dedicated to fencing blade materials aside from proprietary research done by fencing blade manufacturers. The blades used by professional athletes are mostly imported from Europe and very expensive in China, although fencing has become an increasingly popular sport. Most blades used in ordinary fencing clubs and classes in China are fabricated by small metal factories located inland and are of relatively low quality. To address these lacunas, this review paper intends to summarize the development of fencing blade materials and give a glimpse into the future of their development to provide a reference for material selection and process optimization of fencing blades.

The article is organized as follows: First, the different fencing blades, with their requirements in terms of size and functions, are briefly described. The general manufacturing process and performance requirements for the final products are also given. Based on the results from retrospective experiments, two major kinds of blade materials, spring steels and maraging steels, are investigated. The chemical composition, heat treatments, and related mechanical properties of these steels are then introduced. Finally, a review of the basic requirements and current state of the art of blade materials development, as well as possible future directions, are outlined.

2. Basic Characteristics of Fencing Sword

2.1. Sword Types

Three types of swords—the épée, foil, and sabre— are used in modern fencing, as shown in Figure 1 [19]. The shapes, geometries, cross-sections, and flexibilities of the blades differ. Generally, of the three blades, the sabre is the shortest one, with a maximum of 88 cm (34.6 inches) blade length, 500 g (1.1 pounds) weight limit and a rectangular cross-section. It is designed for cutting and hacking as well as stabbing. The medium-sized blade is the foil, a weapon with a rectangular cross-section designed to stab, with the same weight limit of 500 g (1.1 pounds) as the sabre, but its tapering blade is about an inch longer. Finally, the largest of the three is the épée, weighing up to 770 g (1.7 pounds) with a maximum blade length of 90 cm (35.4 inches). It is similar to the foil but has a triangular cross-section [11,20].

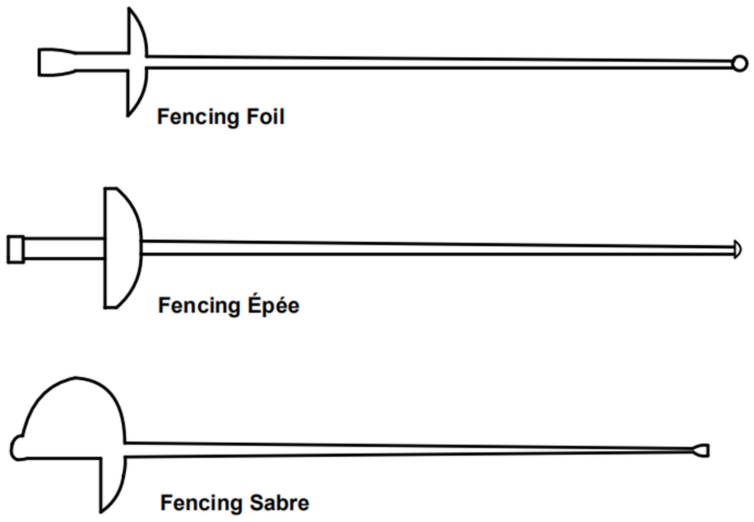

Figure 1. Schematic images of fencing foil-, épée- and sabre-type swords [19].

2.2. Manufacturing Process

The FIE establishes the specific requirements and properties for all three types of blades, and each kind of blade has its own specific design [11]. Nevertheless, the manufacturing

processes of the three blades are similar, with certain differences in specific parameters. Generally, the rough shape of the blade is obtained by machining and cutting in the first step. Then, the blade goes through forgings and heat treatments according to the specific requirements of the blade. The third step is to refine the blade shape and size through mechanical processing. The fourth step is to adjust the microstructure and related mechanical properties through final heat treatment. Finally, surface treatments are done to the blades according to the different requirements for each blade, such as polishing, shot peening, electroplating, etc., to obtain optimal surface properties [21].

For blades made of different steels, the manufacturing parameters have different regulations. As an example, the manufacturing parameters of blades made of GMG steel are provided in Table 1 [11].

Table 1. Manufacturing parameters of GMG steel [11].

Type of Steel	Process
GMG	1. Forging at temperatures between 1150 °C and 950 °C 2. Air-cooling with the blades spaced apart 3. Mechanical machining (removal of extra thickness by reworking) 4. Homogenization at 950 °C ± 10 °C for 1 h 5. Immersion heat treatment at 820 °C ± 10 °C for 1 h 6. Air-cooling with the blades spaced apart 7. Aging at 480 °C for 9 h 8. Air-cooling with the blades spaced apart 9. Cold finishing

2.3. Performance Requirements of Blades

During fencing practice and matches, blades are frequently bent under the tremendous impact force applied when blades strike one another. The blades then recover immediately when the force is removed. Both substantial elastic deformations and possibly plastic deformations are present in blades. Vivaldi et al., demonstrated that impact velocity and deformation velocity have no evident influence on the failure of blades; rather it is the deformation energy and residual plastic deformation that are the cause of fractures [12]. Moreover, the accumulation of low-cycle fatigue damage has also been cited as one of the major mechanisms that lead to blade failure.

An example of the dangers associated with fractures is the tragic death of Soviet fencer Vladimir Smirnov, who was struck by the fractured blade of his opponent [15]. To prevent such fractures, the blade must have high tensile strength, fracture toughness and fatigue resistance. Unfortunately, strength and toughness are generally mutually exclusive. Metallic materials resist crack propagation mainly by intrinsic toughening, which is achieved through the plastic deformation induced ahead of the propagated crack. However, Ritchie addressed this conflict by developing extrinsic toughening, which shields the crack behind the crack tip to limit its propagation rate [22]. This technique may provide a new idea of toughening blade materials through crack deflection or bridging. In addition, since defects introduced during manufacturing, or formed during game play, become the potential nucleus for fatigue failure, manufactured blades need to reduce internal defects and have a surface as smooth as possible.

Aside from the restrictions on shape and weight, a series of mechanical experiments, such as tensile tests, impact tests, hardness tests, etc., need to be carried out on blades used in fencing. The standard mechanical property parameters are shown in Table 2 [11]. For some blades with specific requirements, corrosion resistance, eddy current testing, conductivity and other tests would also be required [21].

Table 2. Mechanical standard of fencing blades [11].

Re (MPa)	Rm (MPa)	A (%)	Z (%)	KCU (J/cm^2)	KIC (MPa $m^{1/2}$)	HV
≥1900	≥2000	≥7	≥35	≥30	≥120	≥500

Re: Yield stress; Rm: Tensile strength; A: Elongation; Z: Reduction of the area; KCU: Impact toughness; KIC: Fracture toughness; HV: Vickers hardness).

3. Development of Blade Materials

3.1. Exploring the Material of the Blade

In the early days, the material used for fencing blades was carbon steel [23]. Because carbon steel is brittle and easily broken during matches, it is only used to fabricate blades which are used as props and decorations at present. In order to investigate the material selection of real fencing blades in detail, two types of blades that are currently used in training and matches were collected. One was produced in China and the other in Europe.

To detect the chemical composition, microstructure and micro-hardness of the two blades, a series of methods were applied. X-ray diffraction (XRD, Smartlab (9KW), Rigaku, Tokyo, Japan) experiments were performed to determine phase and crystal structure. A scanning electron microscope (SEM, Gemini 450, Zeiss, Cambridge, UK), which is attached with an Energy-dispersive X-ray spectrometer (EDS, Ultim 100, Oxford, London, UK) was used to obtain the chemical composition and microstructure. An optical microscope (OM, Zeiss AXIO vert.a1m) was employed to image the metallographic structure. Finally, a micro hardness tester (EM-1000VP, Hengyi, Shanghai, China) was used to obtain the micro Vickers hardness of blades. Five locations were randomly selected in each sample and the average value was taken. The load was 300 g and each loading lasted for 10s.

The XRD patterns of the two blades are given in Figure 2. The results illustrate that the major phase in both blades is Fe, with a body-centered cubic (BCC) crystal structure. Additionally, there is a small amount of FeNi detected in the blade manufactured in Europe. The SEM-EDS results provided in Table 3 show the chemical composition of the two blades. It should be noted that, the light elements (such as C) cannot be detected and quantitative analysis very precisely in EDS, thus the content of C is not included. In comparing these experimental results with the nominal compositions of varied steels, it was found that the blade imported from Europe has a very similar composition as 18Ni maraging steels [24], and the one from China was very similar to Si-Mn series steel. After consulting with Chinese fencing blade manufacturers, it was confirmed that the blade made in China is composed of 60Si2MnA, a kind of spring steel.

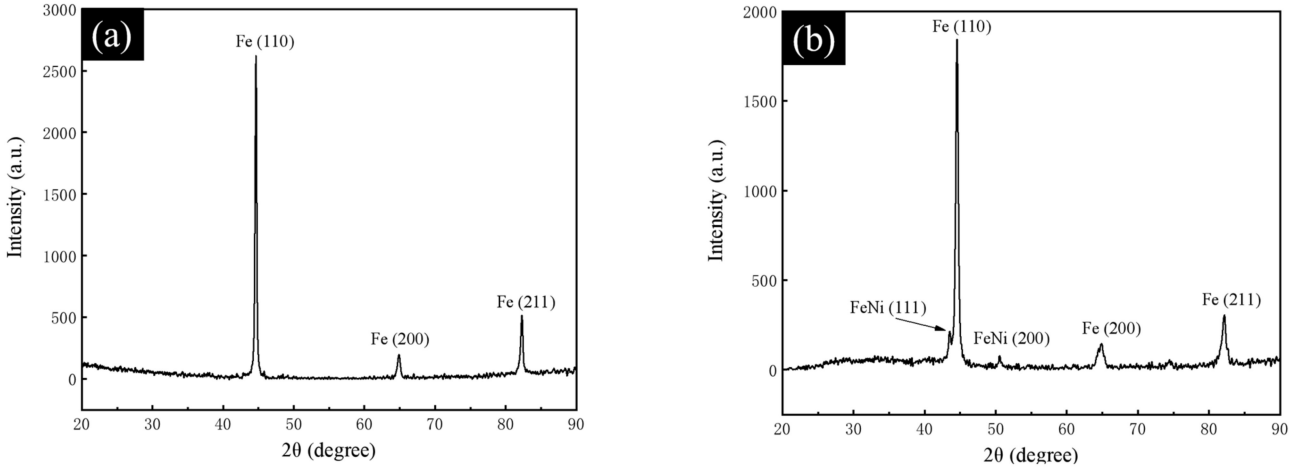

Figure 2. XRD patterns of the two blades. (**a**) blade from China and (**b**) blade from Europe.

Table 3. EDS results of the two blades (mass percent).

Blade Types	Fe	Si	Mn	Ni	Co	Mo	Ti
From China	97.17	1.89	0.94	/	/	/	/
From Europe	66.10	/	/	18.96	8.96	5.24	0.74

Figure 3a,b show metallographic photos of blades from China and Europe, respectively. The structure indicated by the arrow in both images is ferrite. It can be seen in Figure 3a that the spring steel blade (the one made in China) is composed mainly of needle-shaped martensite, residual austenite and a small amount of ferrite, while the maraging steel in Figure 3b is composed of lath-shaped martensite, residual austenite and a small amount of ferrite.

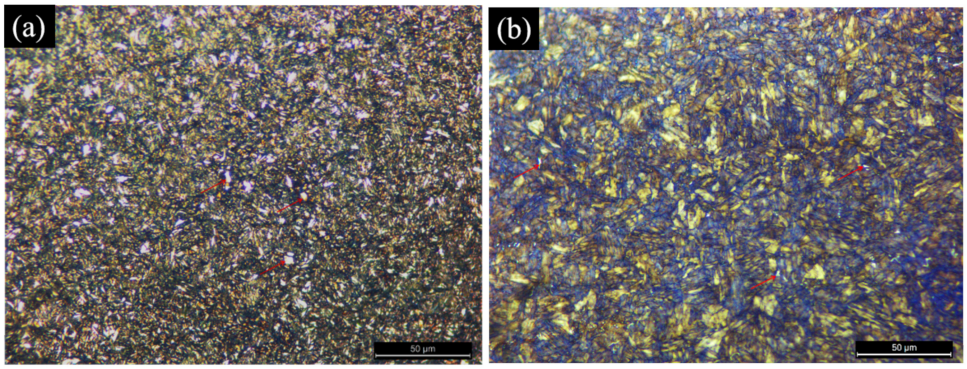

Figure 3. Metallographic structure of the (**a**) spring steel blade, and (**b**) maraging steel blade.

A micro -Vickers hardness test was performed on both the spring steel blade and the maraging steel blade. The results show that the micro-Vickers hardness of the spring steel blade and the maraging steel blade are 478.6 ± 4.4 HV and 608.6 ± 5.5 HV, respectively. The hardness of the maraging steel blade is significantly higher than that of the spring steel blade.

The fracture surface morphology of the two blades is displayed in Figure 4. In the spring steel blade (Figure 4a), the fracture surface is dimpled, with a small number of intergranular fractures and a very small number of quasi-cleavage fractures. In comparison, the fracture morphology of the maraging steel blade (Figure 4b) is pure dimple, indicating better fracture toughness. The characteristics from the fracture surface morphology are consistent with the fact that the toughness of imported maraging blades is better than blades made of spring steel.

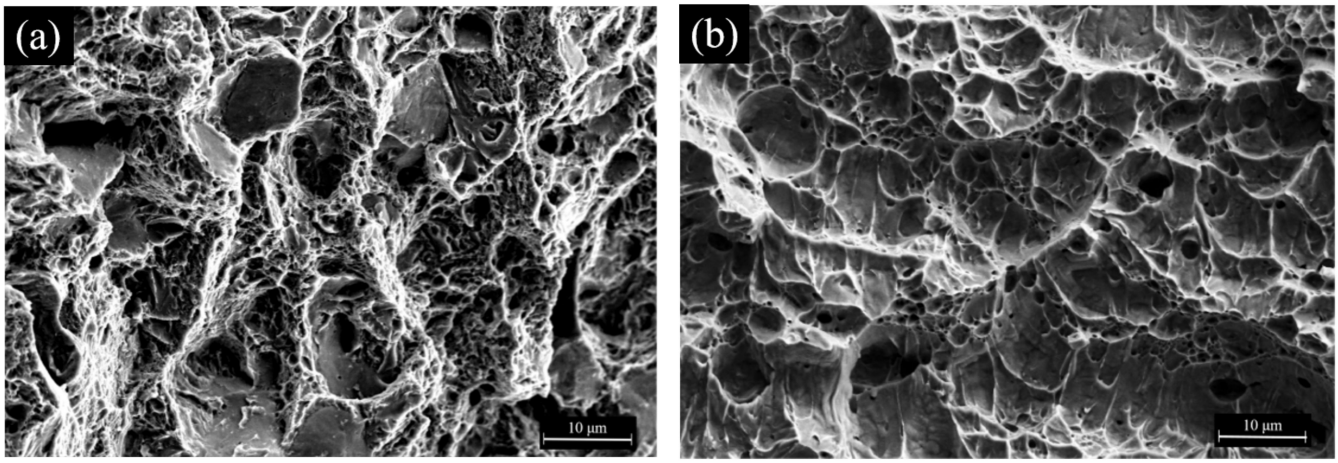

Figure 4. The fractography of the (**a**) spring steel blade, and (**b**) maraging steel blade.

Based on the results of our experimental exploration of blade material, it is clear that the European blade, which is more expensive and usually used in official fencing competitions, is of 18Ni maraging steel system showing better mechanical behaviors. In contrast, the Chinese blade, which is less costly and often used in daily training, belongs to the Si-Mn series and is from the spring steel system. The next section of the paper will provide details of the two steel systems, including their chemical composition and associated heat treatments.

3.2. Spring Steels

Spring steel is a name generically used for a wide range of steels utilized in the manufacture of different products, such as springs and saw blades. These steels are generally medium-carbon steel or high-carbon steel with low-alloyed manganese. Spring steels have high yield strength, tensile strength, elastic limit, and fatigue strength. They are mainly used to fabricate elastic components, that need to bear significant impact load, long-term vibration and alternating stress during the service process. Additionally, spring steels have a high fatigue limit, ensuring that fatigue damage will not easily occur under long-term alternating stress [25–27]. All these characters indicate that spring steels would be suitable for fencing blades, which are subject to many shocks and bends in use.

According to an analysis of the exploratory results, it is clear that the blade from China is made of 60Si2MnA, a typical spring steel. After a search of the literature, two other spring steels, 60Si2CrA and 60Si2CrVA, both of which show high strength, were also found. However, compared to the GMG steel, which has been approved by the FIE, the mechanical behaviors of these three spring steels are still not adequate. The specific parameters of their mechanical properties were collected and are summarized in Table 4 [28].

Table 4. Mechanical behaviors of selected spring steels [28] and GMG steel [11].

Type of Steels (In China Grade System)	Re (MPa)	Rm (MPa)	A (%)	Z (%)
60Si2MnA	≥1373	≥1569	≥5	≥20
60Si2CrA	≥1569	≥1765	≥6	≥20
60Si2CrVA	≥1667	≥1863	≥6	≥20
GMG	≥1900	≥2000	≥7	≥35

Since the properties of steel have an indispensable relation with their composition and microstructures, both of which can be adjusted by heat treatments, the chemical composition, together with the heat treatments of spring steels, are briefly summarized in Sections 3.2.1 and 3.2.2.

3.2.1. Chemical Composition

The carbon content in carbon spring steels is generally between 0.6–0.9 wt.% [29], while the carbon content in alloy spring steel is 0.5–0.7 wt.%. In China, the Si-Mn series is commonly used in alloy spring steels, such as 55SiMnVB, 55Si2Mn, 60Si2Mn. Low-carbon spring steels developed in recent years, such as 28MnSiB, 35MnSiVB, etc. Cr-Mn and Cr-V series are also included in spring steel standards in China, but their prices are relatively expensive due to a lack of required resources available in China [30]. The chemical compositions of the spring steels mentioned above are provided in Table 5 [31].

Table 5. Nominal compositions of selected spring steels (mass percent) [31].

Type of Steels	Fe	C	Si	Mn	Cr	V	S	P
60Si2MnA	balance	0.56~0.64	1.60~2.00	0.60~0.90	≤0.35	/	≤0.030	≤0.030
60Si2CrA	balance	0.56~0.64	1.40~1.80	0.40~0.70	0.70~1.00	/	≤0.030	≤0.030
60Si2CrVA	balance	0.56~0.64	1.40~1.80	0.40~0.70	0.90~1.20	0.10~0.20	≤0.030	≤0.030

The medium and high carbon content ensures that both adequate elastic limit and yield limit can be obtained. To further improve performance, alloying elements such as Si, Mn, Cr, and V are added to improve steel mechanical performance. Both Mn and Si improve not only the hardenability and tempering resistance of the alloy, but also the strength and hardness by solid solution strengthening. However, Si will cause the steel to be easily decarburized during heat treatment, thereby reducing the fatigue strength and wear resistance of the steel. Moreover, Mn may increase the tendency of overheating. Overheating will cause the austenite grains to become coarse, which will seriously impair the strength and toughness of the steel. Thus, a small amount of Cr/W/V can be added to prevent overheating and the decarburization of steel and improve its hardenability [32,33]. It is very important to control the amount of S and P, which can introduce impurities in steels and decrease desired mechanical properties.

3.2.2. Heat Treatment

Appropriate heat treatments can improve the mechanical properties of steel. Spring steel has a high carbon content, and its strength is obtained mainly through solution hardening, transformation strengthening, and grain refining in quenching heat treatment. The structure is mainly high-carbon martensite, resulting in poor plasticity and toughness. Tempered troostite is obtained by tempering at medium temperature, which improves its plastic toughness, but its strength will decrease slightly. The content of Mn and Si function in amending the hardenability and tempering resistance, and through solid solution strengthening, improving the strength and hardness of the alloy. In addition, austempering can also be used to obtain a lower bainite structure to improve the toughness of the steel.

Some experimental explorations have been done aimed at improving the mechanical properties of spring steel via refining the heat treatments. For example, J. Cui et al. [34] austenized 60Si2MnA at 950 °C for 20 min, then oil quenched the sample when it was furnace-cooled to 880 °C, at last, tempered it at 400 °C for 90 min followed air cooling. Through this heat treatment, the structure of tempered troostite was obtained, a mixture of acicular ferrite matrix and dispersed granular cementite. The steel's tensile strength, yield strength, elongation, section shrinkage, impact toughness and Vickers hardness reached 1810 MPa, 1640 MPa, 6.9%, 29.1%, 24 J/cm^2 and 587, respectively.

In the work of J. Zhang et al. [35], 60Si2CrVA was heated to 980–1030 °C and held for 2 h at 1000 °C before rolling. Holding 2 h at 1000 °C is to dissolve carbides fully. The final rolling temperature was 790–820 °C. Then products were austenized at 870 °C for 30 min, followed by an oil quenching, and finally tempered at 420 °C for 1 h. Through such rolling and heat treatment, homogeneous microstructure and crystal grains were obtained, as shown in Figure 5a. The steel's tensile strength, yield strength, elongation and Vickers hardness were 1804 MPa, 1681 MPa, 10% and 543, respectively. As compared, the other sample underwent the same treatment, except that it was not held at 1000 °C for 2 h. Its microstructure is relatively coarse and not homogeneous, as shown in Figure 5b. And its tensile strength, yield strength, elongation and Vickers hardness were 1780 MPa, 1670 MPa, 11% and 538, respectively. The results show that by holding the sample at 1000 °C for 2 h before rolling, a more homogeneous structure can be obtained, so that the strength of the steel is slightly improved.

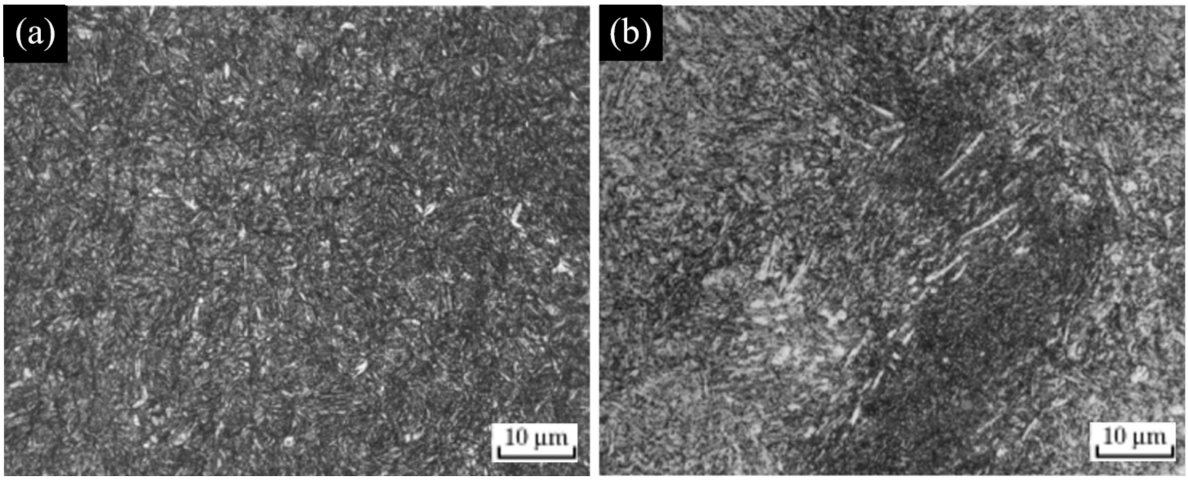

Figure 5. The microstructure of 60Si2CrVA [35]. (**a**) Held for 2 h at 1000 °C before rolling, and (**b**) Without holding at 1000 °C before rolling.

Zhang et al. [36] applied a quenching-isothermal (Q-I) treatment on 60Si2CrVA, and successfully improved its mechanical behaviors. The sample was austenized at 870 °C for 35 min, then quenched in oil at 50 °C for 15 s, then isothermally at 270 °C for 3 h, and finally oil-cooled. This new Q-I treatment resulted in more retained austenite and lower bainite, as shown in Figure 6, which absorbed dislocations and prevented their propagations in the matrix. With this multi-structure, the tensile strength, yield strength, elongation, section shrinkage, impact toughness and Vickers hardness were increased to 2142 MPa, 1804 MPa, 11.57%, 42.17%, 53.75 J/cm^2 and 615, respectively.

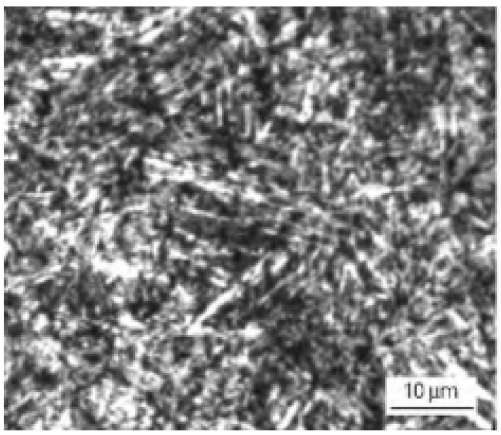

Figure 6. The microstructure of 60Si2CrVA treated by Q-I process [36].

In addition, as medium-carbon and low-alloy steel, the ultra-high-strength 40CrMnSiMoVA demonstrates some mechanical properties which are close to the requirements of the FIE. By adjusting the temperature, duration, and steps in heat treatments, the steel's tensile strength, yield strength, elongation, section shrinkage impact toughness, plane strain fracture toughness and Vickers hardness reached 1981 MPa, 1662 MPa,10.4%, 42.6%, 65 J/cm^2, 71.2 MPa m$^{1/2}$ and 578 respectively [37]. The optimized heat treatment requires the sample to be heated to 920 °C, and then oil quenched to room temperature. A tempering at 260 °C is followed, and the last step is air cooling.

It is obvious that the performance of steel can be improved by modifying the heat treatment process, and the highest tensile strength (2142 MPa from the work of Zhang et al. [36]) has even exceeded the requirements from the FIE (2000 MPa). However, the other parameters still have some gaps with the standards from the Federation. To be approved officially as a material for fencing blades, extensive further research needs to be conducted.

3.3. Maraging Steels

Maraging steels are a special classification of low-carbon ultra-high-strength steels. They have good mechanical properties such as high strength, high fracture toughness and low notch sensitivity. At the same time, maraging steel has the advantage of good cold forming abilities, easy welding and machining, etc. [24,38–40]. Maraging steel can still maintain good performance under high-temperature working conditions, and the highest service temperature can reach 400 °C [41,42]. They were first invented by the International Nickel Corporation in the early 1960s. The principal alloying element is 15–25 wt.% Ni, and secondary alloying elements include Co, Mo and Ti [43]. In the late 1970s, cobalt-free maraging steels developed due to the rising price of cobalt [44]. It was found that cobalt-free maraging steels reduced production costs by 20~30%, and some materials still displayed similar performance as the cobalt-containing maraging steels [44–47].

Both the GMG steel recommended by the FIE [11] and the tested blade from Europe are in the family of 18Ni maraging steels. The mechanical properties of 18Ni maraging steels are given in Table 6 [39,48,49], where grades of maraging steels (250, 300 or 350) are usually related to their strength.

Table 6. Mechanical characteristics comparison of 18Ni maraging steels and GMG steel [39,48,49].

Type of Steels	Re (MPa)	Rm (MPa)	A (%)	Z (%)	KIC (MPa $m^{1/2}$)	HV
18Ni (250)	1655–1825	1690–1860	6–10	35–60	99–165	482–512
18Ni (300)	1790–2070	1825–2105	5–10	30–50	88–143	527–596
18Ni (350)	2427	2468	8	43	40	/
GMG	≥1900	≥2000	≥7	≥35	≥120	≥500

The 18Ni series maraging steel has a very similar chemical composition to GMG (see Table 7) and shows lower fracture toughness. Currently, some manufacturers maintain that maraging steels are the ideal materials for fabricating all three fencing blades [16], although sabers, foils, and épées are different in shape, weight, and size. It indicates that more details, such as the amount of alloying elements, heat treatments, process route, need to be studied in depth.

3.3.1. Chemical Composition

Maraging steels have very low carbon (≤0.03%) and high Ni content [24,50,51]. Some alloying elements such as Co, Mo and Ti and Al are also added to obtain intermetallic compounds precipitations, which form during the aging process and strengthen the steel [52]. In maraging steels, the amounts of impurities are very low, which is achieved by one or two vacuum smelting processes. Table 7 provides the chemical composition of 18Ni maraging steels [24,39,48].

Table 7. Nominal compositions of typical 18Ni maraging steels and GMG steel (mass percent) [24,39,48].

Type of Steels	Fe	C	Ni	Co	Mo	Ti	Al	Mn	Si
18Ni (250) [53]	Bal.	≤0.03	17–19	7.0–8.5	4.6–5.1	0.3–0.5	0.05–0.15	≤0.12	≤0.12
18Ni (300) [53]	Bal.	≤0.03	18–19	8.0–9.5	4.6–5.2	0.5–0.8	0.05–0.15	≤0.12	≤0.12
18Ni (350) [53]	Bal.	≤0.01	17–18	12.0–13.0	3.5–4.0	1.6–2.0	0.10–0.20	≤0.10	≤0.10
GMG [11]	Bal.	≤0.03	18–20	8–13	4.0–5.0	0.5–2.0	0–0.05	≤0.10	≤0.10

The above-named alloying elements function in all properties of maraging steel. Nickel can enlarge the austenite phase region, so in the process of austenitizing heat treatment, more alloying elements can be contained in the austenite. Additionally, nickel functions in inhibiting the formation of pearlite and ferrite [54]. Based on the provided conditions, a supersaturated solid solution can be obtained in the cooling process. Nickel can also increase the dislocation density to improve toughness. Ni_3(Ti, Mo) and other Ni-based intermetallic strengthening phases also contribute to the high strength and hardness of maraging steels [55–59]. However, nickel reduces the martensite transition temperature. When the content of nickel is higher than 18 wt.%, the martensite transition finish temperature will be close to, or even below, room temperature. As well, there will be a large amount of residual austenite after cooling, which reduces the strength of maraging after aging. Therefore, the content of nickel in maraging steels is generally not more than 18% [54,60].

Cobalt is solubilized in the maraging matrix without forming intermetallic compounds [61–64]. Cobalt can increase the martensitic transition temperature of maraging steels, and using an appropriate amount of cobalt can ensure that the martensitic transition temperature is between 200 °C and 300 °C. In this way, complete martensitic structures can form after solution cooling. Moreover, cobalt can inhibit the recovery of dislocations, provide more nucleation sites for precipitated phases, and keep the precipitated particles fine and uniform. The formation of the precipitated phase is thus accelerated, and the time to reach maximum hardness is shortened during aging [52]. Due to the high price of cobalt, many researchers have devoted themselves to the study of cobalt-free maraging steels [48,65,66]. However, attention needs to be given to the unsatisfactory ductility of cobalt-free maraging steels [44].

Molybdenum is added in maraging steels to increase strength and toughness [42,67]. The precipitated molybdenum-containing phase plays a vital role in both enhancing strength and maintaining toughness in the early stage of aging. In addition, adding cobalt can promote the precipitation of molybdenum intermetallic. Molybdenum can also prevent the hardening phase from precipitating along the original austenite grain boundaries, thus avoiding intergranular fracture and improving fracture toughness. However, too much molybdenum will induce residual austenite after cooling, resulting in a decline in toughness.

Titanium is one of the most important strengthening elements in maraging steels and forms the main strengthening phase Ni_3 (Ti, Mo) with Ni in the martensitic aging process [66]. However, with deleterious elements, it can also form inclusions in the matrix, and inclusions are one of the main sources of cracks and microvoids. Thus, the content of titanium should not be too high. In cobalt-free maraging steels, Ti is one major strengthening element to assist cobalt-free maraging steels to attain the same strength level as cobalt-containing maraging steels by forming Ni_3Ti. But the high lattice parameter of Ni_3Ti also leads to a problem that the mismatch with the matrix will decrease the ductility [44]. A further toughening method is thus required.

3.3.2. Heat Treatment

Aging and solution treatments are major heat treatment techniques that can adjust the microstructure and final properties of maraging steels. These treatments introduce the precipitations of dispersed intermetallic compound particles into the martensite matrix, which make the strength of the material increase exponentially with small toughness loss.

The martensitic transformation in maraging steels is not affected by the cooling rate and prevents the hardenability problem that often appears in quenching-tempering steel. The typical heat treatment process is simple and convenient, and the deformations induced by heat treatments are small. The traditional process is as follows. The steel is first heated to 850~870 °C to obtain a fully austenitized structure. Second, air cooling or water quenching to room temperature is performed to obtain the martensite structure. The third step, aging at 480~510 °C for 3~6 h, is used to gain a fine dispersion intermetallic precipitation in the martensite matrix. The process is completed with a final air cooling [54].

Special heat treatment adjustments are sometimes applied to improve the mechanical properties of maraging steels, especially to address the strength-toughness trade-off. For example, the research of Xavier et al., on the solution annealing effect explored the best annealing temperature to increase the fracture toughness with the lowest tensile strength loss [68]. In the study, 18Ni (300) bars were made by vacuum induction melting/vacuum arc refining, hot forged, and solution annealed at 860 °C. Then, samples were sliced and hot-rolled to strips followed by solution annealed for 1 h at different temperatures and cooled in water. Lastly, aging at 480 °C for 3 h.

In comparison, the commercial method to improve the strength of maraging steels is 820 °C solution annealing for 1 h and 480 °C aging for 3 h. The result demonstrates that increasing the solution annealing temperature can improve the fracture toughness but decreases the tensile strength. Solution annealing at 1000 °C is found to be a balance point that can maximize the fracture toughness with the lowest tensile strength loss. The fracture toughness can reach 76 $J/cm^{1/2}$ (26.67% increase compared to the commercial method) with tensile strength 1928 MPa (6.72% lost).

The microstructure of the 18Ni (300) solution annealed at 1000 °C are shown in Figure 7. The austenite grain size is around 30 µm. Compared to 111.8 µm austenite grain size that results from annealing at 1100 °C, the much smaller grain size insures good toughness at 1000 °C annealing. In this process, some carbides disperse into austenite grains and austenite grain boundaries delineate the martensite blocks. The EBSD analysis illustrates that the width of the martensite blocks was around 7 µm. The homogeneously distributed dimples in fractography reflected good fracture toughness from the formation of lath martensite.

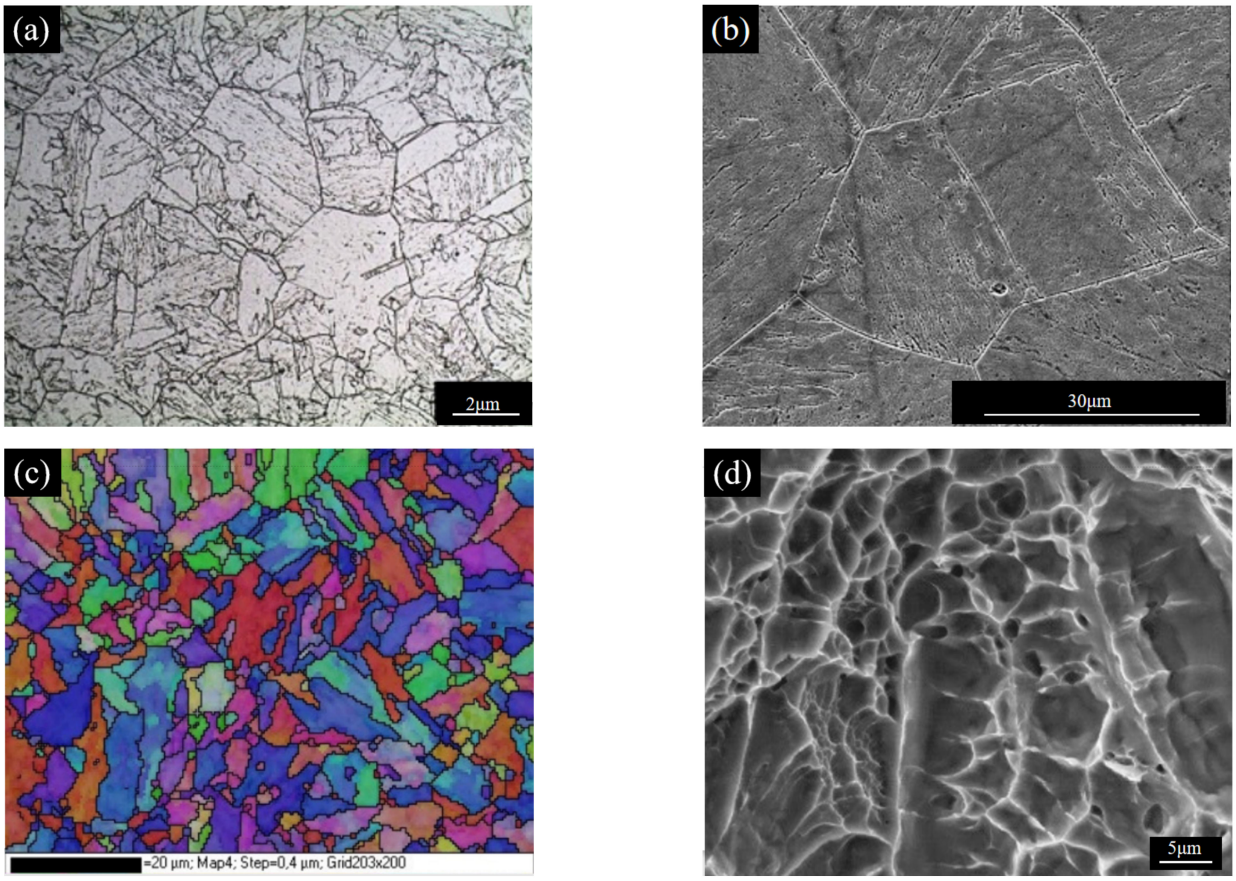

Figure 7. The microstructure of 18Ni (300) solution annealed at 1000 °C [68]. (**a**) Prior austenite grain size; (**b**) SEM images; (**c**) EBSD analysis; (**d**) Fractography.

Next, a special circular grain fining method, proposed by Zhang et al., was applied on 18Ni (250) [69]. After 30 min of solution treatment at 1200 °C, the sample was circular reheated and cooled. The holding temperature remained constant or gradually increased each cycle. The process of cyclic phase change of the sample is shown in Figure 8. Finally, the sample went through 820 °C solution treatment for 1 h and 480 °C aging for 3 h. The results showed that, while ensuring the strength, the ductility and toughness were also increased due to the finer grains and larger aspect ratio of the lath martensite. The steel's tensile strength, yield strength, elongation, section shrinkage and fracture toughness reached 1906 MPa, 1853 MPa, 14.46%, 52.10% and 128.69MPa $m^{1/2,}$ respectively. The microstructure after the variable-temperature circular grain fining process (Figure 9) illustrated that the grain size became finer and more homogeneous after several times of grain fining. This appears to be a suitable process to enhance the strength-toughness combination despite the extra costly heat treatment steps.

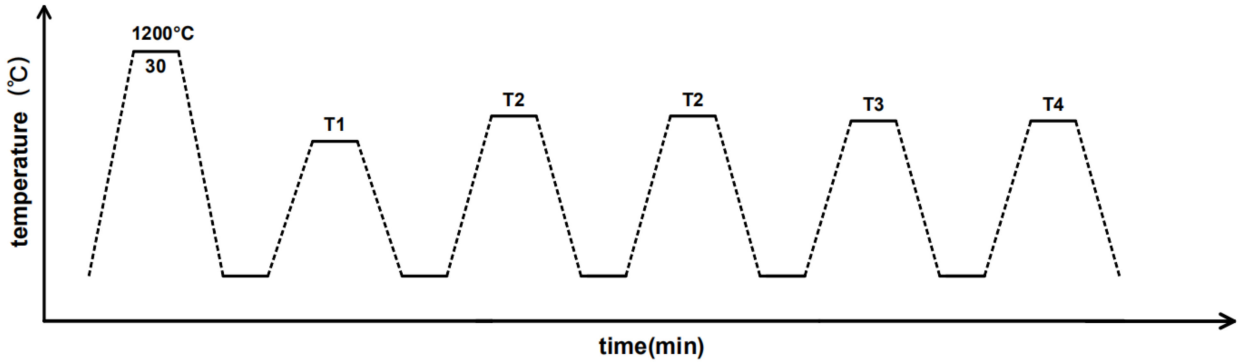

Figure 8. The heat treatment process of the circular grain fining method [69].

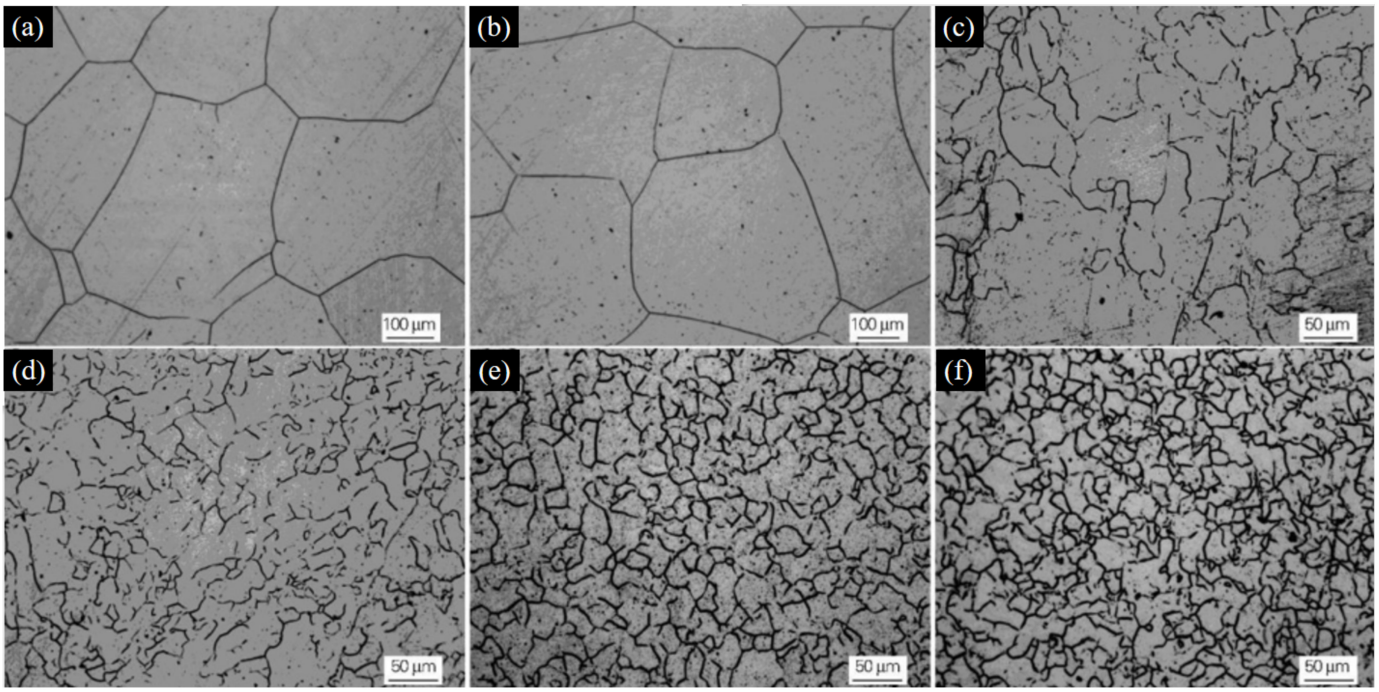

Figure 9. Microstructure of the 18Ni (250) maraging steel after variable-temperature circular grain fining process [69]. (**a**) 1200 °C × 30 min solid solution treatment; (**b**) once grain fining; (**c**) twice grain fining; (**d**) 3 times grain fining; (**e**) 4 times grain fining; (**f**) 5 times grain fining.

He et al., developed a fine process route for Fe-18Ni-4Mo-2.5Ti cobalt-free maraging steels that can obtain a strength rating as high as 2400 MPa [70]. The sample first went through homogenization at 1473 K for 24 h, then air cooling and reheating to 1473 K for an hour. Then forging and rolling the sample at a temperature of 1423 K to 1123 K. Finally, the sample was solution treated at 1083 K for an hour and followed by aging at 753 K for 3 h.

The steel's tensile strength, yield strength, elongation, section shrinkage and fracture toughness reached 2370 MPa, 2330 MPa, 6.7%, 24% and 18.4 MPa $m^{1/2}$. The high strength, which exceeds the FIE requirement for fencing blades, is obtained by the precipitate phase of Ni_3Ti. However, it was usually accompanied by a loss of plasticity, i.e., decreased elongation and section shrinkage. The microstructure in Figure 10a showed that many precipitates with mean diameter of 120 nm were randomly formed in the martensite lath matrix. The fractography showed no cleavage fracture, indicating limited plastic deformation during crack propagation. Thus, small energy absorption leads to low fracture toughness.

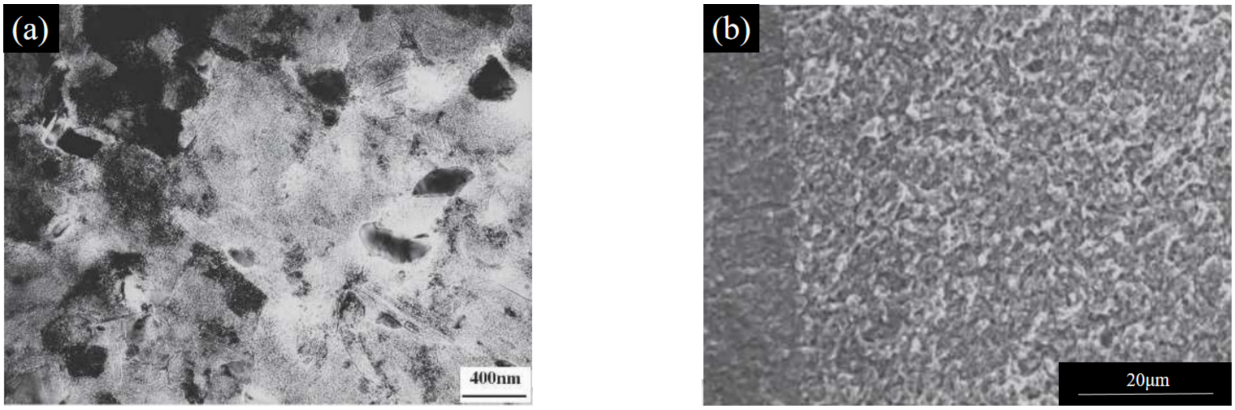

Figure 10. (**a**) TEM bright field images and (**b**) fractography of Fe-18Ni-4Mo-2.5Ti cobalt-free maraging steels [70].

Additionally, He et al. developed a type of 2000 MPa grade Co-free maraging steel with Fe-18.9Ni-4.1Mo-1.9Ti composition [71]. A similar process was applied, i.e., starting with homogenization, forged and rolled at 1123 K, followed by air cooling. Then went through solution treatment at 1073 K for 1 h and quenched in water. The maximum strength was obtained at the 50 h of aging at 713 K. The steel's tensile strength, yield strength, elongation, section shrinkage and fracture toughness reached 2017 MPa, 1957 MPa, 8.0%, 50% and 64 MPa $m^{1/2,}$ respectively. This process decreased the Ti content to sacrifice part of the strength to improve the plasticity and toughness [71]. The fractography (Figure 11) illustrated larger and deeper dimples compared to Figure 10, indicating that the fracture toughness is better. Compared with the FIE standards, its mechanical properties, except for the fracture toughness, are above the standard, proving the feasibility of cobalt-free maraging steels as candidates for manufacturing fencing blades. Few cases of using Co-free maraging steel as blade materials have been reported as yet, and this could be taken into consideration by manufacturers.

Fencing blades made of 18Ni maraging steels can be bent to large angles and quickly recover, which makes these blades favored by elite fencers. The excellent performance of the 18Ni maraging-steel-made fencing blades is inseparable from the composition and microstructure of the blade materials. Mechanisms of alloying elements can be very different, such as through forming intermetallic compounds or dissolving in solid solutions [56,57]. Moreover, the propagation speed of cracks in maraging steels is ten times slower than in carbon steels, which gives maraging blades excellent fatigue resistance [72]. In addition, the fractures of maraging steels are flat, thus the fencer's safety is better guaranteed. However, the price of 18Ni maraging steel might hinder its usage as a common sports tool in developing countries.

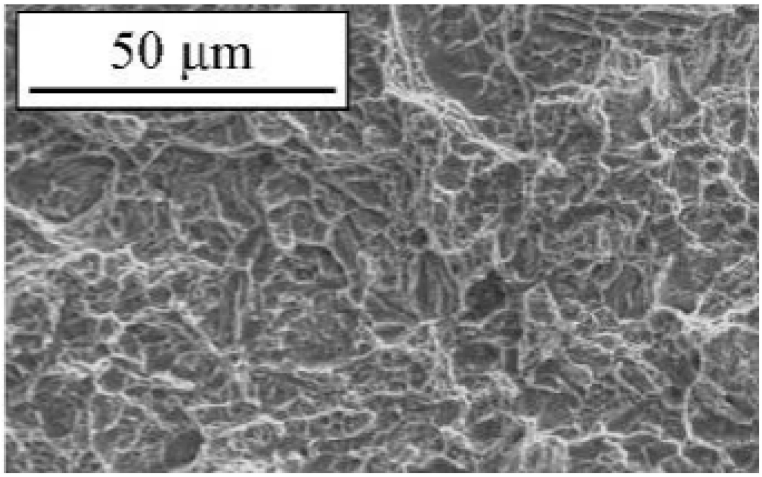

Figure 11. The fractography of Fe-18.9Ni-4.1Mo-1.9Ti cobalt-free maraging steels [71].

4. Discussion and Outlook

4.1. Discussion

Based on the exploratory experimental results and literature analysis, the selected steels, which display the best combination of strength-toughness by using the optimized process route, are summarized in Table 8. However, current strength or toughness still does not fully meet the requirements of FIE standards, and their properties need to be further improved. A brief discussion about each material category follows.

Table 8. The properties of GMG steel and selected steels that may be suitable for making blades for practice or competition.

	Type of Steels	Re (MPa)	Rm (MPa)	A (%)	Z (%)	KCU (J/cm2)	KIC (MPa $m^{1/2}$)	HV	Reference
1	18Ni (250)	1655–1825	1690–1860	6–10	35–60	/	99–165	482–512	[39,48]
2	18Ni (250)	1853	1906	14.46	52.1	/	128.69	/	[69]
3	18Ni (300)	1790–2070	1825–2105	5–10	30–50	/	88–143	527–596	[39,48]
4	18Ni (300)	1912	1928	10.4	17.5	/	76	600	[68]
5	18Ni (350)	2427	2468	8	43	/	40	/	[39,48]
6	Fe-18Ni-4Mo-2.5Ti	2330	2370	6.7	24	/	18.4	/	[70]
7	Fe-18.9Ni-4.1Mo-1.9Ti	1957	2017	8.0	50	/	64	/	[71]
8	60Si2MnA	1640	1810	6.9	29.1	24	/	587	[31]
9	60Si2CrA	1756	1569	6	20	/	/	/	[28]
10	60Si2CrVA	1804	2142	11.57	42.17	53.75	/	615	[36]
11	40CrMnSiMoVA	1662	1981	10.4	42.6	65	71.2	578	[37]
12	Fe-9.95Mn-0.44C-1.87Al-0.67V	1978	2144	19.0	/	/	101.5 (Crack initiation toughness)	/	[73]
13	GMG (meeting FIE standard)	≥1900	≥2000	≥7	≥35	≥30	≥120	≥500	[11]

Firstly, both the European blade and GMG steel show similar chemical compositions as 18Ni maraging steels. In the 18Ni steel family, the strength values of 18Ni (350) are far exceeding the standard, however, its fracture toughness of 40 MPa $m^{1/2}$ is much lower than the standard, 120 MPa $m^{1/2}$. Since strength-toughness is a trade-off, there are some methods that could improve the fracture toughness by losing strength to a certain degree. For example, Xavier et al. [68] combined 1000 °C solution annealing with 480 °C aging increases the fracture toughness with a slight drop in the strength in 18Ni (300) (No. 4 in Table 8). If a properly adjusted chemical composition could be combined with the right optimized heat treatments, Fe-Ni-Co maraging steels are among the best candidates. In addition, the manufacturing parameters of GMG steel indicate that forging might be very useful.

Secondly, for Co-free maraging steels, Fe-(18.0-18.9)Ni-(4.0-4.1)Mo-(1.9-2.5)-Ti provides a good illustration that by slightly changing the heat treatment step and the alloyed element,

fracture toughness can be improved four times, from 18.4 to 64 MPa $m^{1/2}$, with losing only 353–373 MPa in strength. It also illustrates that forging-rolling is a key step in the process to obtain high strength 2000–2400 MPa. However, the required heat treatments are relatively complicated and time-consuming.

Thirdly, spring steels and low alloyed steel have a lower price than maraging steels. However, their strengths are obviously lower than other steels in the list. For example, their yield stress of 1662–1804 MPa, is around 300 MPa lower than that of 18Ni maraging steels. However, forging, rolling, as well as improved heat treatment, can improve their strength further, as Z. Zhang et al. [35,36] demonstrated.

Finally, an ultra-strong steel was reported by Liu in 2020 [73]. It is Fe-9.95Mn-0.44C-1.87Al-0.67V with deformed and partitioned treatment. Its yield strength, tensile strength, elongation and crack initiation toughness reached 1978 MPa, 2144 MPa, 19.0%, and 101.5 MPa $m^{1/2,}$ respectively. Rolling processes in different stages at varied temperatures result in a lamellar martensite/austenite duplex microstructure, which leads to outstanding mechanical behavior. Since its mechanical parameters are the closest to the FIE requirement, and this steel is cost-effective, in principle it might be the best candidate for materials used for fencing blades, although its fracture toughness is still slightly lower than the required standard.

4.2. Future Outlook

In 2020, the number of professional athletes in fencing had increased to 1000 in China, and there are more than 840 registered fencing clubs/units, with 200,000 registered trainers/students. This is four times the number recorded in 2015 [74]. Although currently only GMG steel is approved for blade material by the FIE, fencing blades made from cheaper low-alloy steel are widely used in practice or basic training. For instance, 60Si2MnA, a spring steel, is the major material employed in China. In the same class, 60Si2CrVA presents better mechanical behavior, as Table 8 illustrates. Therefore, 60Si2CrVA might also be used as, or even replace, 60Si2MnA in this area. In addition, the cost-effective steel Fe-9.95Mn-0.44C-1.87Al-0.67V [73], which is reported in 2020 and shows a good balance between strength and toughness, might open new possibilities for manufacturers. Some intensive cooperative research projects between universities and industry might be carried out to improve and apply this material in fencing blades. For example, could additional forging or rolling steps improve mechanical behavior? How can manufacturers balance cost with quality during innovation? etc.

On the other hand, the 18Ni maraging steel can also be improved by adjusting the alloying elements and heat treatments, as well as modifying processes. Then more materials which can meet the requirement from FIE and are dedicated to competition but not training might be dug out. Of course, Fe-9.95Mn-0.44C-1.87Al-0.67V [73] is also a promising candidate in this area.

The selection of blade materials is influenced by such factors as price, technological limitation, and availability of materials, etc., the successful cooperation between manufacturers and researchers will bring more possibilities to meet various requirements on fencing blades in the Chinese industry.

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