Failure Analysis of Fencing Blades

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Abstract. This study deals with the failure analysis of broken fencing blades (one épée and one foil). For the characterization of the broken blades, metallographic examinations, chemical analysis, hardness measurements, fracture surface examinations and tensile tests were performed. Maximum stress occurred at the outer fibres of the blades was estimated as high as 1456 MPa and 1298 MPa for épée and foil, respectively. Results showed that failure of the blades was initiated from a notch, which has been formed as the result of an impact action during training, or from the groove machined along the blade for inserting an electrical wire. In order to increase resistance of the blades against such failures, alternative blade material, modified blade geometry and a surface hardening treatment were proposed.

1. Introduction

Fencing is an art of assault and defence with a sword or similar weapon in which two athletes fight indirectly, through their weapons, and physical contact is forbidden. Modern fencing is a competitive sport of which rules are based on the old-time duelling [1]. There are three main blades used in modern fencing, which are épée, foil, and sabre. There are specific requirements and properties which are determined by FIE (International Fencing Federation) for these three type of blades. Each of them has different technique and target area. Therefore, shapes, geometries, cross-sections, and flexibilities of the blades are different from each other. For instance, foil is rectangular while épée is triangular in cross section. Total lengths of the swords are also different from each other. The maximum length of foil and épée swords is 110 cm each while sabre has a length of 105 cm. In addition to these specifications, there are several testing methods, which are performed on the blades used in Olympic Games and international professional competitions, to determine various properties including ductility, fracture toughness, corrosion resistance, fatigue strength and traction as well as eddy current inspection is also required [2]. Since the blades are exposed to continuous bending during fencing games, they are expected to have superior mechanical properties to ensure a longer life. That is why, it is commonly desired that the blades are resistant to fracture and fatigue [3]. To meet these requirements, maraging steel is mostly preferred material and is used in professional competitions due to its ultra-high strength (up to 2500 MPa), high toughness and fracture toughness. Maraging steel blades are manufactured by forging and are then subjected to a suitable heat treatment, which is an essential step for the blade to gain superior mechanical properties [4, 5]. Heat treatment of maraging steels is a demanding and high cost process which is why the maraging steel blades are very expensive. This leads to the emergence of a need for a cheaper alternative and spring steels stand out

because of their bending resistance and ability to return to their original shape without deforming. Spring steel is started to be used in amateur fencing competitions or trainings as a lower quality alternative to maraging steel. Nonetheless, it has failed at possessing the requirements even for the inferior fencing blades. The blades exhibit poor durability and are broken easily after a short period of usage. Moreover, the lack of standardization for production of lower quality fencing blades makes it difficult to obtain desired properties.

In this study, fencing blades which are used in amateur competitions or trainings were investigated. Fracture analysis was performed on the broken blades to understand what causes the fracture and to offer a solution to this problem.

2. Experimental Procedure

Swords which have been taken from ITU Fencing Club were examined. Some of the swords were broken during trainings or competitions as shown in figure 1. Duration until breakage can vary depending on the quality of blades. The higher the quality, the longer will be the durability of the weapon.

**Figure 1.** General view of a broken blade (épée).

In order to determine the properties of the swords and to obtain detailed information; chemical, microstructural, and mechanical analysis were performed on épée and foil blades. Firstly, chemical analysis was done for both épée and foil blades by optical emission spectroscopy (GNR Metal Lab Plus, Italy) to identify the blade material. Before chemical analysis, one sample for each blade was cut from the close-handle sections of the blades and they were sequentially cleaned in boiling water and alcohol. For microstructural analysis, two samples for each blade were cut from the tip and handle sections of the blades and were mounted by epoxy resin at 160°C under a pressure of 98 MPa. The samples were gently ground and polished by using SiC papers (with successive use of 400, 600, 800, 1200, 2500 grid emery papers) and alumina suspensions (with 1 μm and 0.3 μm particle size and 200 rpm rotating speed). The mirror finished samples were examined by an optical microscope (Leica ICC 50 HD, Germany) before etching to determine whether there are inclusions. Then, etching was applied to the samples by using 5% nital solution. When microstructural analysis was completed, hardness measurements of the samples were carried out by hardness tester (Zwick/Roell ZHR, Germany). The hardness scale was selected as Rockwell C using a normal load of 150 kgf (1471 N) and a diamond cone indenter. The measurements were repeated as five times for each sample and the values were averaged. Surface defects and fracture surfaces of the broken blades (an épée and a foil) were examined by a digital microscope (Cooling Tech, China) and a scanning electron microscope (Hitachi TM 1000, Japan) in back scattered mode. Stress analysis was performed on an épée and a foil blade to reveal the stresses occurred on the blades. For this purpose, bending stresses exerted on the outer fibers of the blades were estimated by stress – deflection equations. Tensile tests were carried out to determine tensile strength of the blades and to compare it with the results of the stress analysis. One

specimen with approximately 20 cm in length for each blade was cut from the close-tip sections. Test was performed once for each blade with a constant cross head speed of 2 mm per minute. Tensile strength was calculated by dividing the maximum load to the cross sectional area of the blade at the point of fracture.

3. Results

### 3.1. Chemical Analysis and Structural Characterization

Chemical analysis by optical emission spectroscopy revealed that blade materials are 56Si7 quality spring steel according to EN 10132-4 standard [6]. Figure 2 shows as-polished optical micrographs of the samples. It is clear that blade microstructures contain some non-metallic inclusions which are spherical in shape and possibly belong to oxide inclusions. Etched optical micrographs of the samples were shown in figure 3. Both épée and foil blades have almost the same characteristic features in their micrographs. They have a ferritic–pearlitic microstructure close to the handle, while contain martensite phase close to the tip of the blades which are frequently exposed to impact during competitions. It clearly suggests that a quenching heat treatment has been applied to the tip of these blades.

(a)   (b)
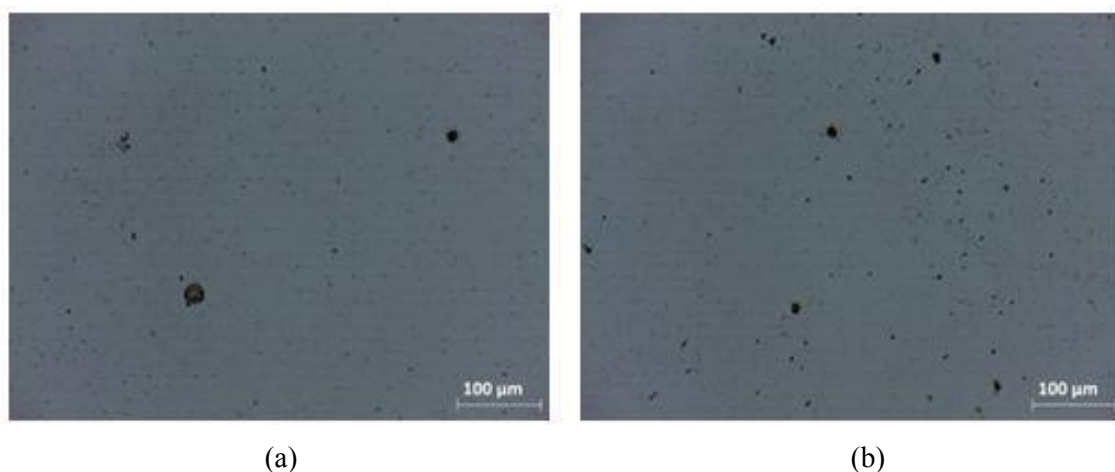
Figure 2. As-polished optical micrographs of the blade materials (a) épée, (b) foil.

Hardness values, measured from the handle and the tip sections of épée were 25 and 56 HRC, respectively. Similarly, the foil has a hardness of 33 HRC at its handle and 59 HRC at its tip. Measured hardness values from different sections of the blades were in well agreement with the microstructural characteristics observed in the corresponding sections of the blades shown in figure 3a and b.
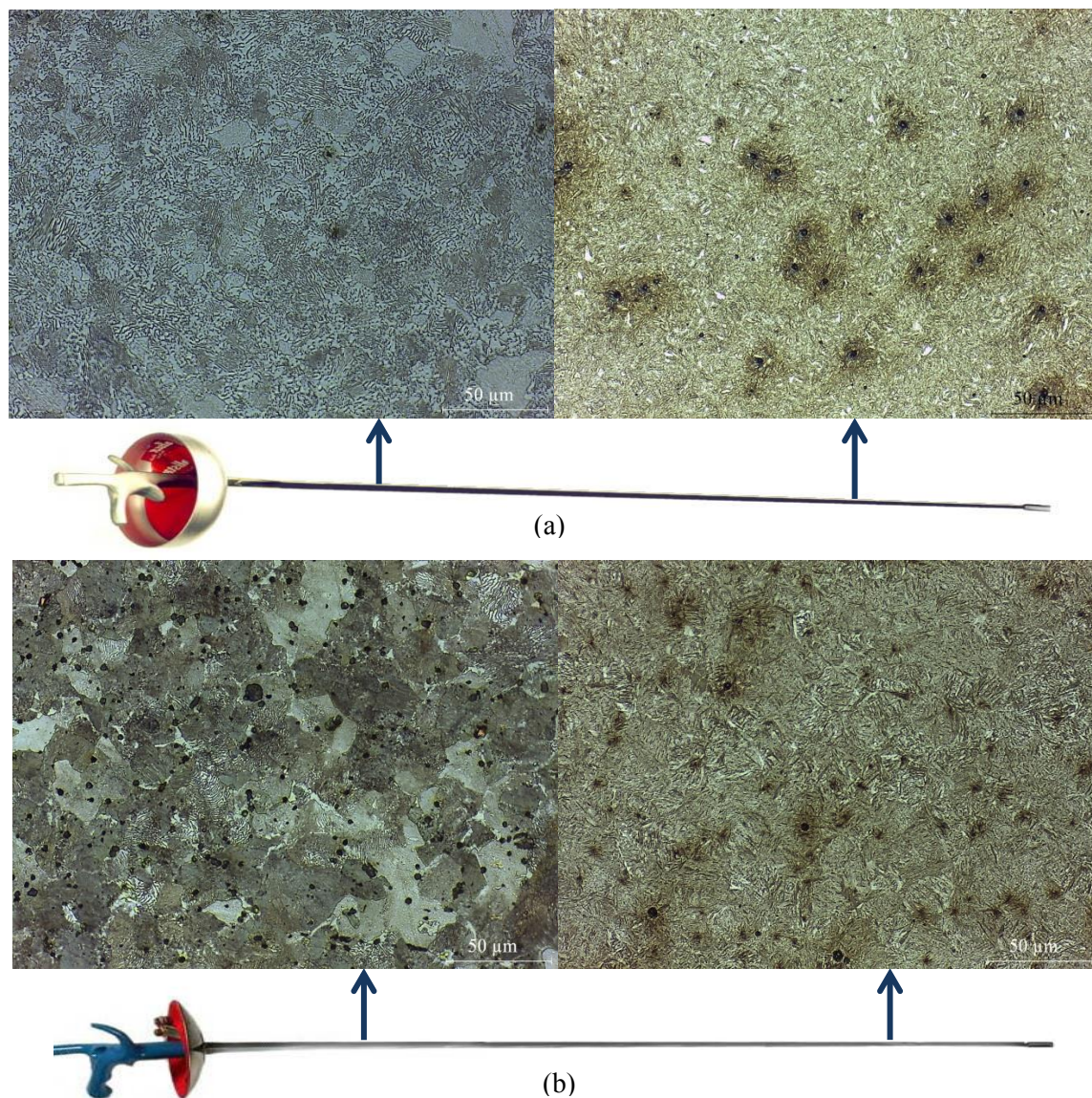
Figure 3. As-etched optical micrographs of the blade materials (a) épée, (b) foil.

3.2. Fracture Surface Examinations

Figure 4 shows surface flaws and general view of fracture surfaces of the investigated blades. Location of the surface flaws shown in figure 4a and b were at the edges of the blades and possibly resulted from the opponent's strikes during training. These types of defects are capable of leading fracture of the blades by initiating a crack due to notch effect. Figure 4c and d demonstrate that the cracks can also be originated from the grooves, where stress concentration is high. It can be observed that fracture characteristics of both épée and foil were brittle in nature without exhibiting any significant plastic deformation as shown in figure 4c and d. SEM fractographs shown in figure 5a and b revealed that general characteristics of the fracture surface were mixed mode fracture which contains intergranular brittle fracture and dimple areas.
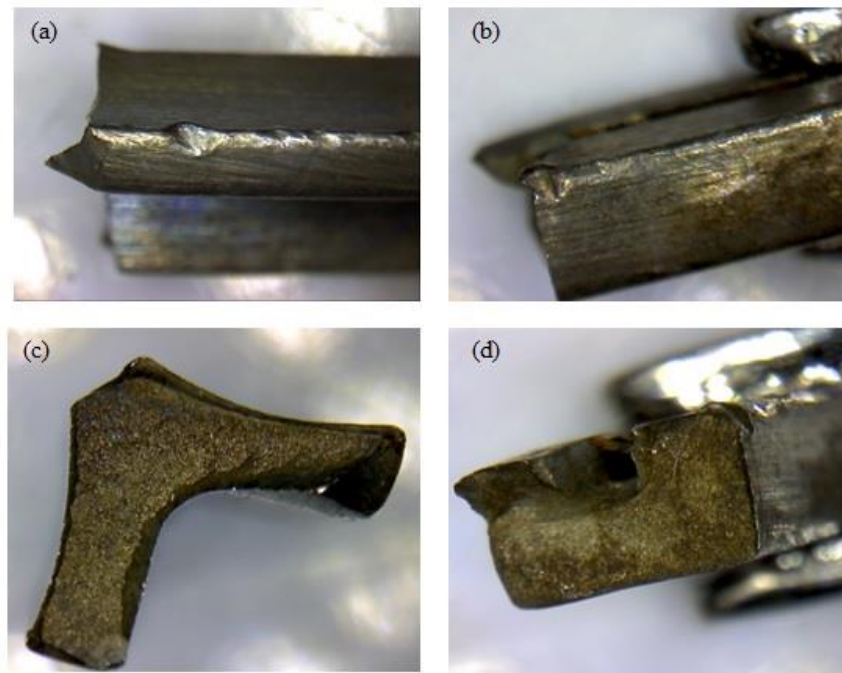
Figure 4. Surface flaws on the surface of (a) épée, and (b) foil, and general view of fracture surface of (c) épée and (d) foil.
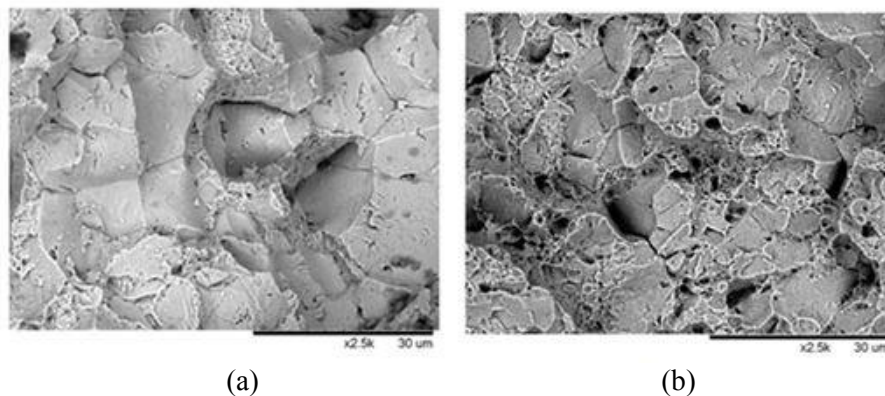
**Figure 5.** SEM images of the fracture surfaces of (a) épée, and (b) foil.

3.3. *Estimation of Stress Exerted on the Blades*

In order to estimate maximum stress exerted on the blades during competition, the blades were first forced to be bent by a fencer as much as a real competition (figure 6). In this loaded condition, maximum deflection of the blades was measured. Assuming that deflection of the blades in this loaded configuration is symmetrical along the length of the blades, bend radius was calculated and the corresponding tensile stress at the outermost fibers of the blades was estimated according to equation (1)

$$\sigma = \frac{E \cdot Y}{R} \qquad (1)$$

where σ is tensile stress, Y is distance from the neutral axis, E is modulus of elasticity (210 GPa) and R is bend radius. Based on this approximation, maximum stresses which are exerted on the outermost fibers of the blades were estimated as 1456 MPa and 1298 MPa for épée and foil, respectively [7].

| (a) | (b) |
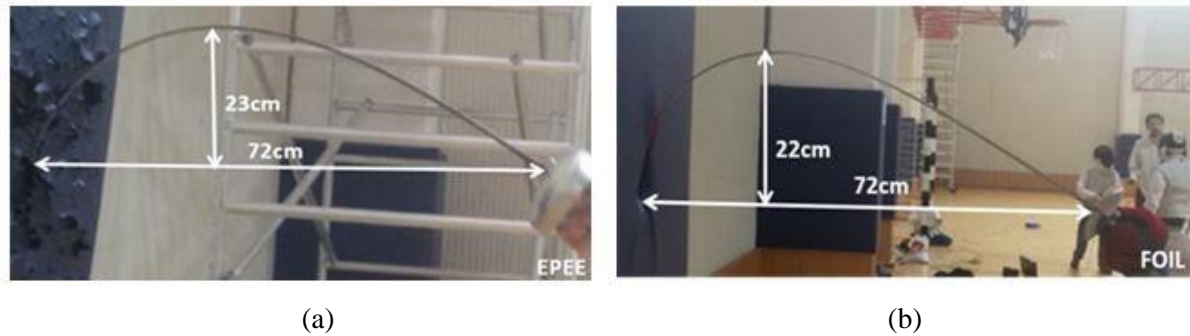
Figure 6. Bending of blades during attack, (a) épée and (b) foil.

    It is clearly shown by the above calculations that very high stresses are exerted on the surface of the blades during a real competition. In order to resist such high stresses, the blades should be made of a material with a very high strength, as described in the previous sections. Tensile strength of the blades were determined as 1538 MPa and 1939 MPa for épée and foil, respectively. When these values are compared with estimated stress values exerted on the blades, it is clear that maximum stress is close to the tensile strength of the blades. It also dictates that it is critical to choose a very high strength material to prevent a sudden failure during fencing.

4. Discussion

As presented in the previous sections, very high stresses, which are comparable to tensile strength of the material, can be produced during a fencing attack. It is therefore likely to be occurred a sudden fracture of the blades, which might be dangerous for the fencers. In order to prevent occurrence of such a failure, a previous research suggests a steel − steel composite (martensite fibers in a tough austenite phase) [3]. In this study, on the other hand, three approaches - selecting a very high strength material, modifying the geometry of the blade or modifying the surface of the blade materials - were developed to eliminate the problem. Details of these suggestions were given in the following subsections.

4.1. Alternative Material

Precipitation hardened stainless steels, which are a group of very high strength steels, were suggested to be an alternative material for high strength fencing blades. Well known member of this alloy is 17-4 PH whose name stems from the additions of 17% Cr and 4% Ni. This steel also contains 0.3% Nb and 4% Cu. Mechanical, chemical and physical properties of precipitation hardening stainless steels are similar to those of maraging steels [8]. That is why, they can meet the requirements for a high strength fencing blade. Nevertheless, 17-4 PH steels are almost as expensive as maraging steels since they have similar heat treatment process, yet they are still considerable alternative despite the high cost.

4.2. Modifying the Blade Geometry

As stated in Section 3.2, cracks in the fencing blades can be originated by the notches on the surface or from the groove machined along the blades. Therefore, modifying the blade geometry by changing the depth of the groove, through which the electric wire passes, was suggested to prevent occurrence of high stress concentration on the blades. This can help reducing the stress concentration factor (K_t). Typical cross sectional view of a foil is shown in figure 7. According to equation (2) it can be clearly seen that h value considerably affects K_t value [9]. When groove depth is decreased from 1 mm to 0.4

mm, K_t value decreases from 2.79 to 1.94. This change corresponds to 30% decrease in stress concentration factor and minimizes the possibility of crack initiation from the groove.
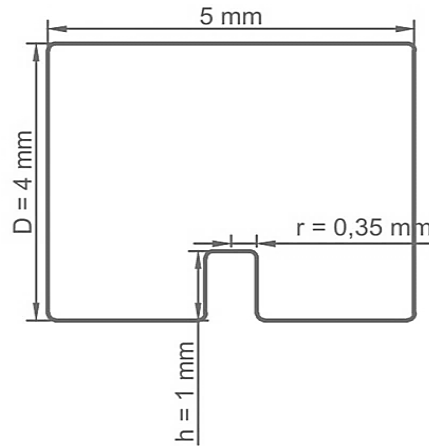
Figure 7. Schematic cross-sectional view of the foil.

$$K_t = C_1 + C_2 \left(\frac{h}{D}\right) + C_3 \left(\frac{h}{D}\right)^2 + C_4 \left(\frac{h}{D}\right)^3 \tag{2}$$

h is groove depth, D is thickness of the foil and C_1, C_2, C_3, and C_4 are parameters determined by h/r ratio. Before the modification, since h/r ratio (2.86) was in between 2 and 20, C values are calculated through equation (2.1-2.4);

$$C_1 = 2.966 + 0.5 \left(\frac{h}{r}\right) - 0.09 \left(\frac{h}{r}\right)^2 \tag{2.1}$$

$$C_2 = -6.475 - 1.126 \left(\frac{h}{r}\right) + 0.019 \left(\frac{h}{r}\right)^2 \tag{2.2}$$

$$C_3 = 8.023 + 1.253 \left(\frac{h}{r}\right) - 0.02 \left(\frac{h}{r}\right)^2 \tag{2.3}$$

$$C_4 = -3.572 - 0.634 \left(\frac{h}{r}\right) - 0.01 \left(\frac{h}{r}\right)^2 \tag{2.4}$$

After the modification, since h/r ratio (1.14) was in between 0.5 and 2, C values are calculated through equation (2.5-2.8);

$$C_1 = 1795 + 1.481 \left(\frac{h}{r}\right) - 0.211 \left(\frac{h}{r}\right)^2 \tag{2.5}$$

$$C_2 = -3.544 - 3.677 \left(\frac{h}{r}\right) + 0.578 \left(\frac{h}{r}\right)^2 \tag{2.6}$$

$$C_3 = 5.459 + 3.691 \left(\frac{h}{r}\right) - 0.565 \left(\frac{h}{r}\right)^2 \tag{2.7}$$

$$C_4 = -2.678 - 1.531 \left(\frac{h}{r}\right) + 0.205 \left(\frac{h}{r}\right)^2 \tag{2.8}$$

4.3. Surface Hardening

Another solution to prevent failures of the blades can be surface hardening of the blades by a proper heat treatment to increase their resistance to fencer's strikes. For this purpose, the proposed heat treatment is nitriding without formation of a brittle white layer. It can be carried out by forming nitride layers composed of S-phase which is a metastable nitrogen supersaturated phase on the surface and it is possible to apply it to spring steel with either gas or plasma nitriding methods [10]. By means of

nitriding, formation of notches on the surface of the blades becomes more unlikely and fracture possibility decreases.

5. Conclusion

This study was undertaken to contribute the existing information and to provide some metallurgical insights on the blades used in fencing sports since there are few works available in the literature concerning material characteristics of such equipment. Hardness of the blades in near tip sections were determined in the range of 56-59 HRC while near handle sections had a hardness of 25-33 HRC. Failure of the blades was originated from the surface flaws formed as a result of fencer's strike or from the grooves machined along the blades for inserting the electrical wire. Tensile stresses exerted on the blades were estimated as high as 1456 MPa and 1298 MPa for épée and foil, respectively, based on maximum deflection which can be possible during a real competition. Tensile strength values of épée and foil were determined as 1538 MPa and 1939 MPa, respectively. Since maximum stresses occurred on the blades were very high fraction of tensile strength, it was therefore concluded that very high strength materials such as 17-4 PH stainless steels should be used for manufacturing the blades. On the other hand, it was proposed that blade geometry can be modified in such a way that stress concentration around the groove can be minimized. Finally a proposed heat treatment, namely S-phase nitriding without the formation of a brittle white layer, might be performed to increase resistance of the surface against the formation of crack inducing flaws during fencing.

Acknowledgements

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