Sword Material Selection and Processing: A Modern Engineering Perspective

1 – Introduction

Weapons have been a fundamental element of many martial arts since their birth. Many martial arts incorporate weapons into their styles, historically to aid in training soldiers for battle. As martial arts developed through history some styles started to reduce their dependence on weapons, conversely, some branched into focusing only weapons – famously the Okinawan Kobudo. All armed martial arts require a high quality of weapon to be reliable throughout its use. These weapons are subject to extreme forces and stresses, requiring a high level of manufacturing. One such weapon is the sword. Swords have been used internationally for thousands of years, with many different regions developing their own techniques and preferences. This essay will discuss the material selection and considerations from a modern engineering perspective.

2 – Materials Selection Process

Selecting a material for the blade of a sword requires first defining critical characteristics. For a sword blade, it is required that the blade be sufficiently strong – that is that its *yield stress*, σ_y, is relatively high. The yield stress is the critical stress at which the material begins to yield – that is the elastic limit of the material. If the stress increases past the yield stress, permanent *plastic deformation* occurs. For a blade, this would mean that the blade could lose its overall shape and be bent more easily. It also means the edge would dull more easily. The material also ought to be reasonably stiff. Stiffness of a material is measured by the *Young's modulus*, E. This governs the deflection of the material given an applied force. *Fracture toughness*, K_{IC}, is also an important property for a sword blade. This defines a materials ability to resist fracture – a low fracture toughness leads to a brittle material – a blade must be able to resist repeated impacts on a variety of materials, requiring a high toughness. Finally, hardness, which is the material's ability to resist localised surface deformation is required – a relatively high hardness will prevent the edge from denting and chipping easily.

To help select a suitable material, material selection charts may be used. These comprise of two material properties plotted against each other on the x and y axis, with material groups then mapped in the axis space. Figure 1 shows a plot of Young's modulus against strength. For a sword blade, a material from the upper right quadrant is required. Polymers and natural materials may be ruled out instantly – with both groups offering relatively low strength. Some woods can offer significant stiffness, and when acknowledging density, the *specific* stiffness and strength can be comparable to some metals, especially oak. However, due to the granular structure of woods, they are considered *anisotropic*, in that the properties depend on the direction of the grain. For example, with the grain, oak's specific stiffness is comparable to metals such as zinc, nickel and magnesium. However, across the grain, these properties can fall by more than 50%.

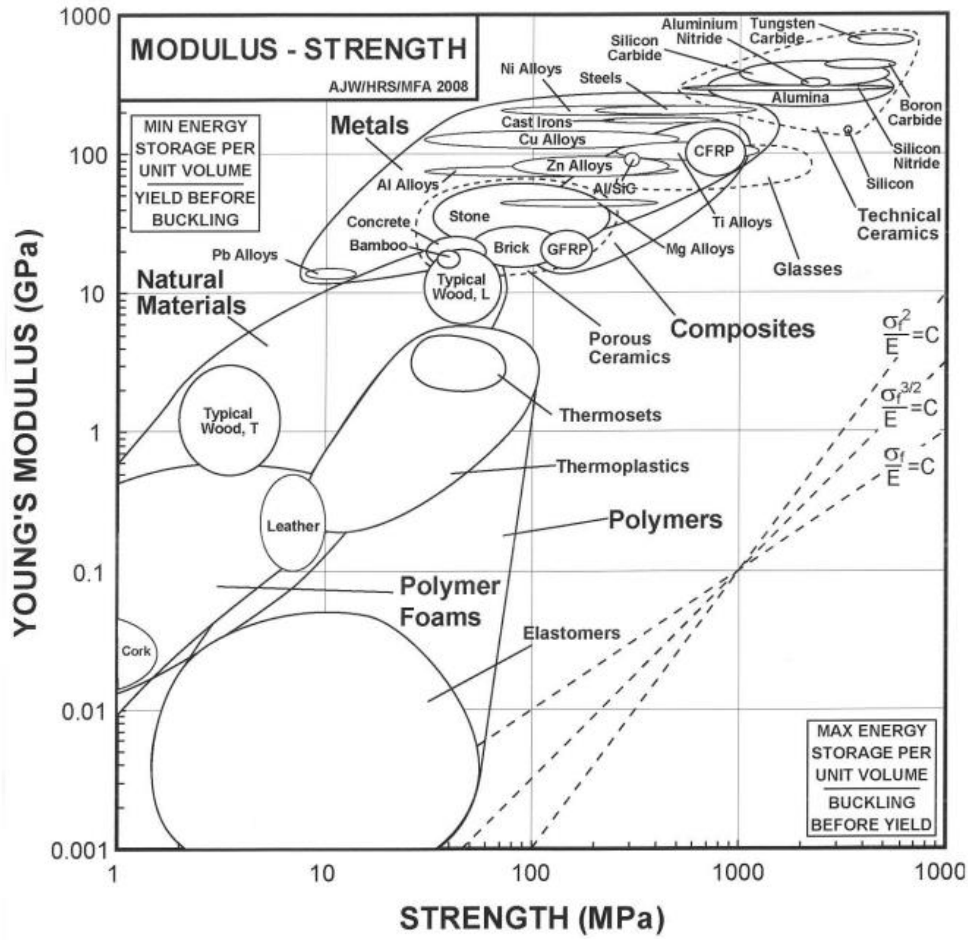

Figure 1 A plot of Young's modulus against strength

The metals, technical ceramics and glasses groups show potential on this graph. Notable examples include steels, titanium alloys, tungsten carbide, alumina and glass. An important property of technical ceramics is that, similarly to concrete, their strength is only significant in compression. This means that in bending and in tension, ceramics lose their strength. When considering a sword blade, most of the gross structural load will likely be in bending, meaning a ceramic blade could be more likely to fail more easily.

Next, the fracture toughness may be plotted against strength. This may be seen in figure 2. From this chart, glasses may be ruled out due to exceedingly low fracture toughness (~ 100 more brittle than steels). The y-scaling on this graph shows the metals group more separated out and its constituents more clearly visible. From this expanded view, it is shown that stainless steels, low alloy steels, carbon steels and titanium alloys are all viable options, all offering significant strength and toughness. However, when considering manufacturing a sword, titanium can be incredibly difficult to forge, causing significant wear to the dies and equipment in use. Alternatively, machining titanium is also problematic – its low heat conductivity causes heat to build up at the machining site, causing damage to the tooling and unwanted hardening and phase changes. For these reasons, titanium may be eliminated from the selection.

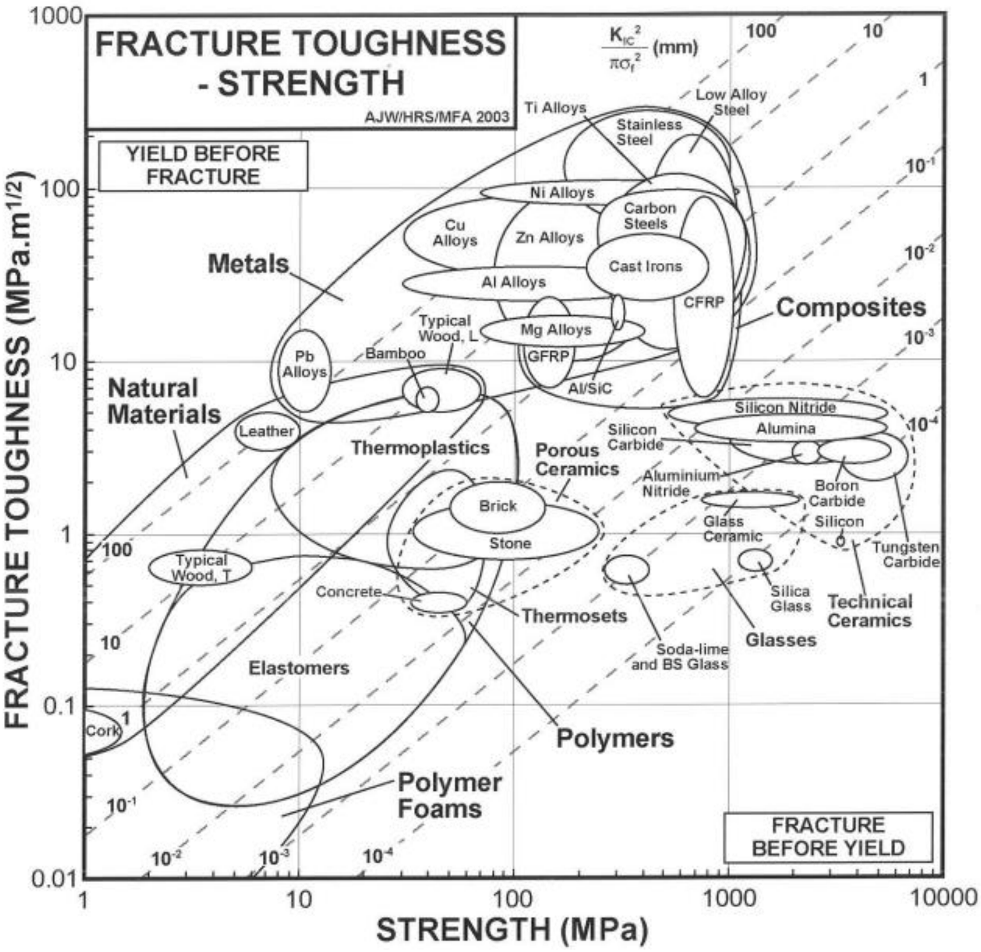

Figure 2 A plot of fracture toughness against strength.

Next, material hardness may be considered. There are many ways of measuring material hardness, a popular method being the Vickers Hardness Test – this involves pressing a precisely sized and cut diamond with a precise force into the surface of a material, and then carefully measuring the size of the indent created. Stainless steel is a steel alloy which includes $> 11\%$ chromium. Its most notable property is that it is corrosion resistant and offers a self-healing ability due to this chromium content. However, it is relatively soft when compared to carbon steels. It also does not offer the processing ability of carbon steels (this will be discussed in detail below). For this reason, stainless steel cannot hold an edge well enough for blade and can therefore be eliminated.

After these considerations, carbon steels are shown to be a suitable material. They offer significant stiffness, strength and fracture toughness with the ability to finely tune the hardness via heat treatments. They are also relatively inexpensive when compared to other metal alloys and technical ceramics.

3 – Steels

Steels are iron-carbon *alloys* containing a relatively low percentage (by weight) of carbon, typically between 0.05 wt% (weight-percentage) to 2 wt%. Alloys with 2 wt% to 4 wt% are considered cast irons. The mechanical properties of a steel are greatly dependant on both the carbon composition (and any other alloyed elements) and the processes carried out on the steel.

3.1 – Composition

All materials can exist in different *phases*. A simple example of a phase change would be that of water boiling into steam, or freezing into ice – the liquid water, solid ice and gaseous steam are considered the phases of water. When multiple elements are alloyed together, this can create a spectrum of possible phases, by varying both the composition of the alloy and the temperature, different phases become available. This is best displayed in a *phase diagram.*

The phase diagram for iron-carbon alloys is shown figure 3. The x-axis shows the percentage, by weight, of carbon and the y-axis shows the temperature of the alloy. Each section on the diagram denotes a different phase of the alloy. The mixture of different elements means the phases associated with each element may mix in various ways – therefore multiple regions on the phase diagram are present.

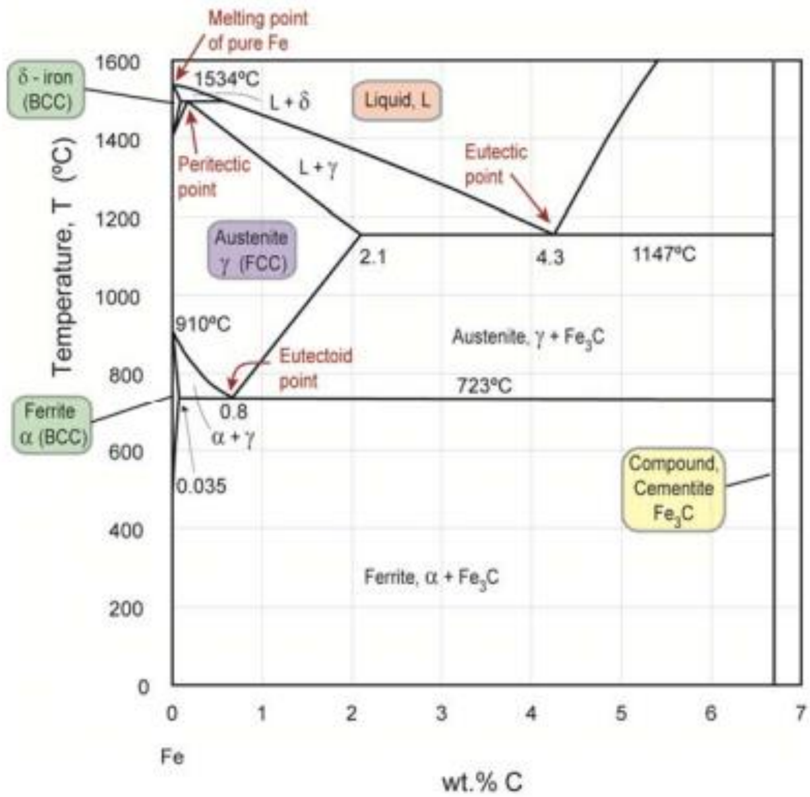

Figure 3 The phase diagram for iron-carbon alloys.

When considering steels, only the first section of this phase diagram is relevant (see figure 4). Typically, swords require medium to high carbon steels (> 0.3 wt%C). This high carbon steel allows for *austenite* to be formed at a lower temperature (closer to the *eutectoid* point labelled in figure 4). This phase causes the atoms to rearrange into a *face-centred cubic* pattern. This means that there is more volume for the carbon atoms to be absorbed into. Once cooled, the composition directly defines the *microstructure* of the steel.

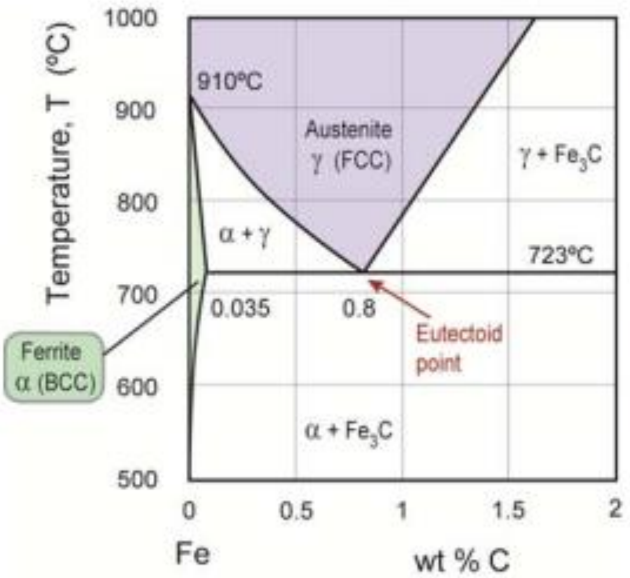

Figure 4 The steels section of the iron-carbon phase diagram.

3.2 – Microstructure

The microstructure of the steel defines the physical properties of the steel. To control the microstructure, the steel can be processed in different ways. Once the carbon content has been fixed, the material must be cooled. If the material is cooled slowly, i.e., left to air cool, the phase will transform as expected from the phase diagram in figure 4. The austenite grains will slowly have crystals of *ferrite* form between them. Since the material is cooling slowly, these crystals become quite large. Below 723°C, the remaining austenite transitions into *pearlite*. This pearlite forms as thin layers of ferrite and *cementite.* This produces a soft and ductile steel, which is not useful for a cutting blade – this would not hold a sharp edge and would easily bend and yield when used. However, when a sword is forged, this process is necessary and is known as *normalising.* This allows the grains to reform themselves and alleviate any stresses and fractures that may have been introduced into the blade during the forging process. This normalising cycle of heating and slow cooling is often repeated multiple times.[1]

After the blade has been normalised, the stresses and defects have been removed but the blade is still soft. To counter this, the steel may be cooled rapidly in a process called *quenching*. This involves heating and then quickly submerging the blade in water (or oil – oil is less thermally conductive, giving a slightly slower cooling rate, which may be required for some scenarios). This rapid cooling does not give the carbon time to diffuse and produce the pearlite layers. Below 723°C, the austenite is not stable. Due to the high carbon content, the steel is considered *supersaturated*.

[1] Note – sometimes this process of stressing the metal can be advantageous. When a metal is cold forged, and the blade is struck multiple times, this has the effect of *work hardening*. This was the method used to harden bronze swords.

Once the steel is below $230°C$, *martensite* begins to form. This forms when the strain reaches a critical limit in the austenite and the crystal structure shears into the new structure, martensite. This is an extremely quick process, with the martensite forming a needle shaped crystal, travelling at the speed of sound (~ 7000 mph in steel). Once at room temperature, the majority of the unstable austenite will have transitioned to martensite. The slowest cooling rate which will produce 100% martensite is known as the Critical Cooling Rate (CCR). The steel must be cooled at this rate or quicker in order to achieve the desired result.

This martensite steel is incredibly hard but also very brittle. This makes it useful for some tooling applications as it can hold an edge well. This hardness is due to two mechanisms – solid solution hardening and dislocation density. Solid solution hardening occurs here due to the excess carbon in the lattice structure. These carbon atoms spread throughout the microstructure and break up the uniform structure and help to stop *dislocations* progressing through the material. The materials dislocation density is also increased, this means it is more difficult for dislocations to move as they become tangled together – this increases the strength of the material (this is the same mechanism that work hardening utilises). These same properties also cause the martensite to be very brittle – because the dislocations cannot move through the material, the material is therefore prone to fracture. In the context of a sword blade, this would mean that the slightest impact with a harder material would cause the blade to crack and fail catastrophically. Additionally, any existing defect in the blade would quickly leas to fracture due to the low fracture toughness (see equation 4 in section 4).

To solve this issue, steel may be heat treated again in a process called *tempering*. This is the process of heating the steel to a lower temperature ($< 540°C$), being careful not to enter the austenite phase. This low heating process encourages crystals of cementite to precipitate in the steel while the martensite relaxes into ferrite. However, the existing needle-like crystal structure, now with precipitates of cementite, provides a very hard material via a mechanism called precipitation hardening, which, similarly to solid solution hardening, prevents the movement of dislocations throughout the material. This new “tempered martensite” structure is around twice as hard as the slow cooled steel (produced from the normalisation process). Whilst it is not as hard as the initial martensite, it is approximately ten times tougher, meaning the new material is not brittle.

This material, offering great hardness and toughness, is an ideal material for a sword blade. The hardness allows the steel to retain an edge, whilst the toughness means that any damage or cracks will not propagate through the blade and cause complete failure.

3.3 – Differential Heat Treatment

In traditional Japanese sword manufacturing, many of the same principles are used, however, a unique technique called differential heat treatment also exists. Once the blade is forged into shape and normalised, clay is added to the spine of the blade but not the edge. The blade is then heated into the austenite phase and quenched. During the quench, the cutting edge of the blade cools very quickly, allowing martensite to form. However, the clay insulates the spine of the blade, meaning it cools at a much slower rate. This allows the carbon to diffuse through the metal and reach an equilibrium state more slowly, allowing pearlite to form. This combination means that the cutting edge is incredible hard – harder than most European steels and many other general use steels. However, the edge is still brittle, so can be prone to chipping and cracking. The spine of the blade is now a relatively soft steel (compared to the edge), but is much more tough than the edge, meaning cracks cannot propagate through the thickness of the blade. Additionally, the method of quenching the blade allows for a curve to be added, as seen in many traditional Japanese swords. When the blade is quenched, the blade is dipped edge first. The rapid cooling of the edge causes it to contract and shrink, bending the blade in a concave manor. This is then followed by the slow cooling of the spine of the blade, which then pulls the blade into the traditional convex curve. The increased mass in the spine of the blade allows more stresses to build up – overpowering the initial curvature.

4 – Shaping a Blade

4.1 – Cross Sections

When designing a sword blade, a simple analogy would be to consider the blade as a cantilever loaded in bending. An ideal blade must be able to resist permanent damage, both to the structure and edge, during loading. This loading would occur when the blade meets significant resistance, i.e., from armour, another weapon, or a thick bone. To simplify this problem, the blade shall be considered during static equilibrium. This does not represent the transient response to the impulse (the most likely loading scenario) but does provide an estimate. The deflection of a loaded cantilever is governed by equation 1, where W is the applied force, l is the distance between the support and the applied force, E is the Young's modulus and I is the second moment of area of the structure.

$$\delta = \frac{Wl^3}{3EI} \tag{1}$$

The most notable property here is EI, which together are known as the *flexural stiffness*, where E offers stiffness from the material and I offers stiffness from the shape. The second moment of area, I, is calculated by integrating the square of the distance from the neutral axis with respect to the area. Simply put, the more material away from the centre of the cross section, the stiffer the structure (this is why I-beams are shaped as they are – the flanges offer more stiffness the further they are from the centre). It is important to note that non-symmetrical cross-sections offer different second moment of areas in different directions – you can easily bend a ruler in the flat sided direction, but not along the measuring edge. From equation 1, it is shown that the larger the flexural stiffness of the blade, the less deflection there is.

A blade such as a rapier, which has a thin, diamond cross section, is designed for stabbing. The small cross section and second moment of area mean that they bend very easily and to a large degree, but the thin blade also decreases the mass of the blade, giving excellent tip control. For a larger blade, like a claymore, bending is undesirable, especially in the direction of the edge. The blade is also double edged, meaning a reinforced spine is not possible either. Swords like these will often have a fuller (groove) down the centre of the blade. By forging this groove down the centre, more material is pushed away from the centre of the blade (see figure 5), increasing the second moment of area (in both directions) and therefore increasing the stiffness of the blade, without increasing the mass. For a traditional Japanese curved blade, there is only one cutting edge. This means more material may be used in the spine of the blade to increase the second moment of area and therefore the stiffness.

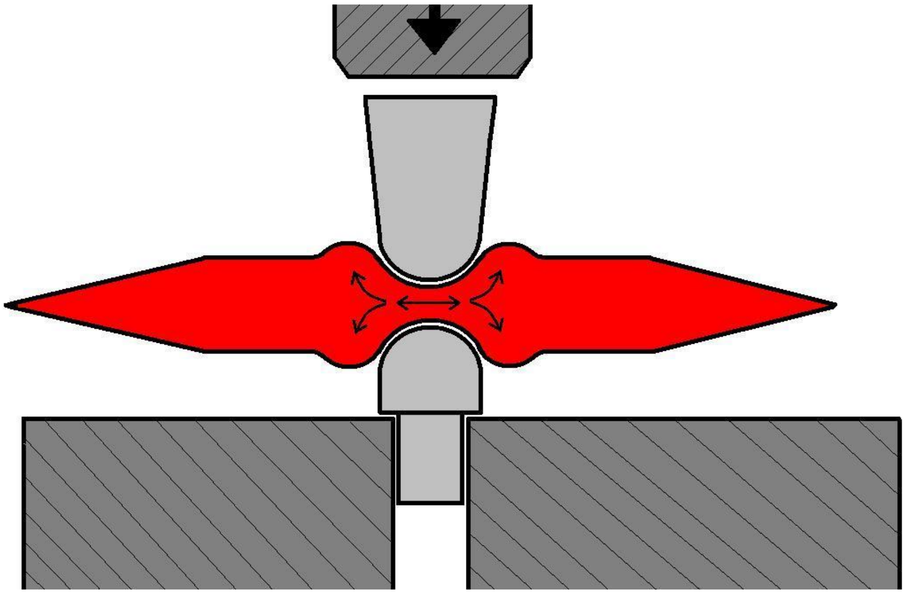

Figure 5 Die forging a fuller into a blade.

4.2 – Failure Modes

When considering failure modes for a sword, one possible mode could be simplified to buckling when stabbing. For this failure mode, equation 2 may be utilised. This is known as the Euler buckling equation – it provides an estimate for the maximum compressive force, P_E, a column can resist before buckling. From equation 2, it may be seen that the maximum load is inversely proportional to the square of the length of the blade, L. This is an important note as for a thrusting sword, reach is important, requiring a large L, but too long, and the sword will buckle. Again, an increased flexural stiffness will aid in reducing buckling. Note this is a form of elastic failure.

$$P_E = \frac{\pi^2 EI}{L^2} \tag{2}$$

Another possible failure mode could be yielding at the root of the blade, again considering the blade as a static cantilever, equation 3 may be used. Here, the failure is more dependent on the yield stress (strength), σ_y, of the material. In equation 3, y is the distance between the neutral axis (the centre on a symmetrical blade) and the edge. This shows that highest stresses build in the edges of the blade. Note, with a sufficiently strong material, failure in this mode is unlikely to occur before buckling or cracking, however a check is required.

$$P_f = \frac{\sigma_y I}{yL} \tag{3}$$

Another common failure mode could be fast fracture. Fracture mechanics is an extremely complex and broad topic. Considering a basic crack being pulled apart (similar to what would be expected in bending), equation 4 may be used. Here, K_{IC} is the failure stress intensity factor and is a property of the material. Typically, a low K_{IC} means a brittle material. The localised stress, σ, is applied by the bending and or movement of the blade and a is the crack length. A harder blade helps to resist the initial forming of cracks and reducing the size of any cracks, therefore helping to reduce a. This means a blade of the same fracture toughness (K_{IC}) may resist higher stresses (due to smaller cracks) before fracturing.

$$K_{IC} \approx \sigma\sqrt{\pi a} \tag{4}$$

5 – Conclusion and Limitations

In reality, a sword blade is a very dynamic system with multiple mechanisms at play simultaneously. This analysis has not included any mechanics of motion or vibration analysis. Both these play a significant role in the behaviour of a system. The analysis given here has primarily investigated the material considerations and mechanisms of choosing an appropriate blade material. This analysis showed that a hardened medium to high carbon steel offers the best compromise of material properties. Other metals may be used but some properties would be sacrificed. The failure of a blade as a structure is also an incredibly complex system, however the equations and discussion above give good indications of important properties and characteristics of a blade.

6 – Glossary of Terms

Alloy *– An alloy is a mixture of multiple elements, including at least one metal.*

Anisotropic *– When a physical property has different values depending on the direction in which it is measured (As opposed to isotropic).*

Austenite *– A high temperature phase of steel.*

Cementite *–* Fe_3C*, iron carbide. A hard, stable phase of steel.*

Dislocation *– A line defect in a materials lattice structure.*

Eutectoid *– A composition which has the minimum temperature between the solid mixture phase and solid solution phase. This is denoted by a "V" shape in a phase diagram.*

Face-Centred Cubic (FCC) *– A crystalline repeating unit cell structure in which atoms are centred on the faces of the unit cells (as opposed to one atom centred in the middle of the cell in body-centred cubic (BCC)).*

Ferrite *– Also known as alpha phase, this is a phase on the iron-carbon phase diagram. This is a ferrous magnetic phase.*

Flexural Stiffness *– Defined as* EI*, this is a term used in structural engineering and mechanics to combine both material and shape caused stiffness.*

Fracture Toughness (K) *– The ability of a material to resist failure by fast fracture.*

Martensite *– A very hard, needle like crystalline structure of steel.*

Microstructure *– The grain structure of a material at the microscopic scale.*

Normalising *– The process of slowly heating and cooling a metal to encourage phase changes to help release pre-stresses and defects in the material.*

Pearlite *– A mixture of cementite and ferrite which forms in a layered structure.*

Phase *– A region in which a materials properties are mostly uniform.*

Phase Diagram *– A 2D plot of temperature against composition for a mixture of two elements showing the possible phases.*

Plastic Deformation *– Deformation in the plastic region of the material – this is permanent, and the energy used to deform the material cannot be recovered (as opposed to elastic deformation).*

Specific *– In terms of materials properties, a specific property is that property divided by the density.*

Supersaturated *– When a solution contains more of a solute than it can fully dissolve.*

Tempering *– A hardening process for metals consisted of slowly heating and cooling the material.*

Work Hardening *– A process of hardening a metal by repeatedly deforming it at low temperature.*

Yield stress (σ_y) *– A critical stress of a material at which yielding, or permanent plastic deformation, first occurs.*

Young's Modulus (E) *– A measure of elasticity and stiffness of a material.*