Stress Fatigue in Iaido Blades

Abstract

It is common knowledge that any sword used in combat or *tameshigiri* can potentially break. For most people it is virtually inconceivable that a sword could break cutting nothing but air. In this paper we discuss possible causes for the latter type of sword failure. To avoid confusion we shall define three groups of swords. Using direct and hearsay evidence we will focus on one group and identify a particular type of sword. Possible causes for sword failure will be introduced. Three likely possibilities will be examined further: flaws in fabrication, properties of the alloy, and improper *hasuji*. Finally, we shall present an actual case study where a sword catastrophically failed and our conclusions on what caused the failure. A glossary of Japanese terms is on the last page.

Three Sword Groups

Historically, various types of swords have been used and misused in *Iaido*: *shinken*, *iaito*, *mogito*, *gunto*, *showato*, *gendaito*, *shinsakuto*, etc. For this paper we shall define *Iaido* as only performing *katas* and *suburi* with a sword (cutting nothing but air). In an attempt to avoid confusion, we will over simplify and categorize swords into three groups: *shinken*, *iaito* and *kazarito*.

Shinken are real swords made out of steel. S*hinkens* are hand forged and folded and are differentially tempered in the traditional manner. These swords are only made in Japan and only by a licensed smith. To obtain a license today requires a minimum, five year apprenticeship, culminating in forging a quality sword before a panel of judges (senior smiths). This certification allows a smith to forge a maximum two swords a month. These swords can be used for both *Iaido* and *tameshigiri*. These swords include traditional antique *katanas*, as well as modern *shinsakutos*. *Shinsakutos* start at around $6000.00 from a newly licensed smith.

[Author's Japanese shinken, forged in 2009 (strange color is due to reflection)]

Iaito (*mogito*) are constructed for the sole purpose of practicing *Iaido*. They are not designed for metal on metal contact and should never be used for *tameshigiri*. They are usually made to appear the same as a *shinken* except for being lighter weight. The mass adoption of the *iaito* is a direct result of Japan's unconditional surrender at the end of World War II. Beginning in 1945 it was illegal to own and manufacture swords as well as practice martial arts in Japan. The American occupation forces confiscated thousands of swords. They were stored in warehouses, destroyed and given away as souvenirs. In 1950 the *Bunkazai-hogo-ho* took effect and swords deemed to be culturally important or national treasures were preserved. In 1951 the Japanese Firearms and Sword Law (*Ju-tô-hô)* was adopted that required all swords to be licensed by the government. On September 1, 1953, regulations were implemented that allowed licensed smiths to forge a limited number of traditional made steel swords.

The limitation on production dramatically impacted their price. *Iaito/mogito* made from Zn/Al alloy were specifically exempted from this restriction.

Iaitos/mogitos were identified as training and decorative swords having a zinc-aluminum (Zn/Al) alloy blade that can't be sharpened. Zinc is the predominant metal in a Zn/Al blade. Today the possession of a steel sword in Japan without proper registration is a criminal offense punishable with a fine of ¥300,000 and/or up to three years imprisonment. It is for these reasons that the majority of *Iaido* is practiced using a Zn/Al alloy *iaito*.

Outside of Japan, *iaitos* can be made with different alloys and even steel. Examples include Aluminum alloys where Al is the predominant metal, *e.g.,* Duralumin, aluminum-beryllium. A variety of steel alloys exist as well, *e.g.,* 400 series stainless, T10 high-carbon, spring steel, etc. Some of these steel *iaitos* are even forged and folded, providing the user the balance and weight characteristics of a *shinken* at a fraction of the price.

[Author's Steel Iaito, forged in 2011]

Kazarito is a "display sword". These swords should <u>never</u> be used for practice or *tameshigiri*. These swords can be made from any metal or alloy including steel or aluminum. These swords vary in appearance from a costume sword to something virtually indistinguishable from an *iaito*. *Kazarito* tend to be garish with ornate patterns on the *saya*. The tsuka-ito is often very thin, loose, or the diamond pattern is not even or distorted. Some believe that a *kazarito* can be identified when the *tsuka-ito* weave matches the *sageo*. The *tsuka* and *same'* are often made of plastic. The blade is usually chrome plated, very shiny, with a very even wavy *hamon* etched on to it. These swords are made all over the world, even in Japan.

[eBay--$42.99, 4pc Deluxe Dragon Katana Samurai Sword 3pc Set w/stand]

Stress Fatigue in Iaido Blades

The Evidence

There is evidence that one type of sword does break 'cutting nothing but air'. The author's Zn/Al *iaito* failed, details of which are found in the case study below. [CET 2013] related to the author that while in Japan he witnessed a 'big guy' break his *iaito* demonstrating *Ryuto* with an incorrect angle (bad *hasuji*). A quick search on the Internet (excluding instances of abuse) also revealed that Zn/Al *iaitos* break.

Zyranyth on [FA 2006] related how three different *iaitos*, two of which were Tozando, broke in Finland over the last 20 years. Ari-Matti Saren on [SFI,2006] confirmed these accounts and provided additional information. One *iaito* was about 2-*shaku*, 4-*sun* in length by an unknown manufacturer and it broke at the *mune-machi*. Upon examination he observed a 'bubble' at the crack site. The second was a new Tozando Dotanuki *iaito* about 2-*shaku*, 7-*sun* in length, with no known mis-use which cracked right behind the *machi*. The third case involved Mikko Oksa who was using a Tozando Dotanuki *iaito* about 2-*shaku*, 8-*sun* in length, with no known mis-use and it cracked at the *mekugi-ana*. According to Ari-Matti Saren all breaks happened when the then *kyu*-level *iaido-ka* stopped the sword at the end of *kirioroshi*.

Michael Hodge an assistant instructor at Mu Mon Kai dojo in Toronto Canada [JCCC 2007] commented how after hearing some snapping and cracking noises his iaito broke cleanly through the *mekugi-ana* during class.

Brad from [KW 2012] explained how one of his students had an issue with a Tozando Minosaka low end *iaito.* It was found to have had a small pressure crack/wrinkle at the *ha-machi*. It was sent back for a refund. DCPan posted on [KW 2012] that he knew a local *iaido-ka* who has broken two Japanese Zn/Al *iaitos* in the last 12 years. Kokoro777 [KW 2012] witnessed two Zn/Al *iaito* failures in two years in England. The first failure was the dojo's senpai and the other was Martin Clark at Solihull. Kim Taylor from the University at Guelph [KW 2012] wrote that 15-20 years ago he broke a Japanese Zn/Al *iaito* inside the *tsuka* doing a *yoko giri* cut.

Ken Goldstein from Hawaii [NMB 2011] witnessed both his Sensei's and another student's *iaito* break during practice. He actually had to jump to avoid his Sensei's blade as it came whizzing along the floor at him.

Although rare, *iaitos* do break. The above list included both *kyu*- and *dan*- level practitioners. All cases were from Zn/Al alloy *iaito.* No evidence could be found of a *shinken* or a steel *iaito* breaking 'cutting nothing but air'. Furthermore, where identified, the Zn/Al *iaitos* seem to fail at the *machi* or the *mekugi-ana*. Why are these *iaito* failing?

Possible Causes for Iaito Failure

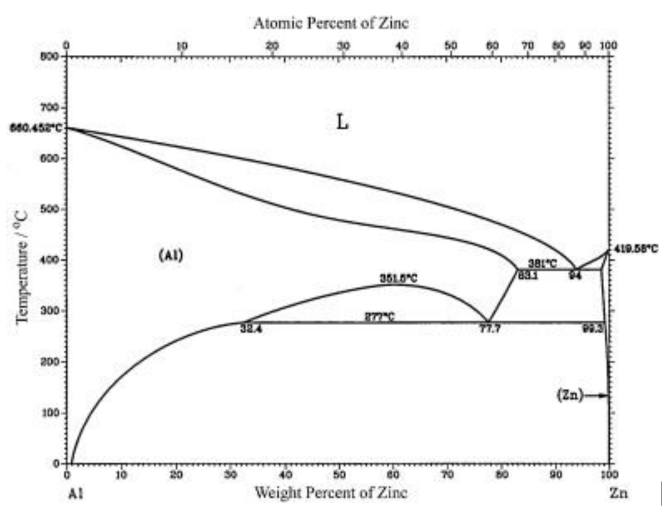
A definitive explanation for the cause of any of the above Zn/Al *iaito* failures is not possible for a variety of reasons. The primary reasons are the proprietary nature of the process and the inability to inspect and test the various steps of the process. But we can take basic engineering principles and formulate an educated opinion. Possible causes include, but may not be limited to: Flaws in the design/geometry of the blade; Flaws in the design/use of the 'permanent' casting mold for the blade; Errors in the casting process; Limitations of the alloy; poor craftsmanship in the final stages in sword fabrication and assembly; finally abuse and or mis-use of the finished *iaito* (improper *hasuji*). To the extent we can, we shall look at each of these possibilities in turn.

Stress Fatigue in Iaido Blades

An in-depth analysis of the design/geometry principles inherent in a Japanese sword are beyond the scope of this paper. Hundreds of years of experimentation and testing in war have ‘optimized' the design of a cutting sword in Japan. The author only feels competent in commenting on one aspect of the design, *i.e.*, the *bo-hi*. Blades with a *bo-hi* are not stronger than a blade without. They have virtually the same strength in the vertical, see *hasuji*, direction only. In engineering, a solid beam of moderate length is stronger than an I-beam with the same external dimensions. I-beams are used in buildings and bridges because they have better strength/mass ratio. The purpose of a *bo-hi* is to reduce weight, adjust balance, potentially hide *kizu* and to produce *tachi-kaze*. Most *iaitos* have a *bo-hi* and the *mune-machi* usually cuts into the *bo-hi*. This fact will become important when we discuss fatigue below.

Quality Zn/Al *iaitos* are cast using reusable molds, so-called permanent molds. It is unknown to the author if they are using gravity, low-pressure or a vacuum process. Permanent molds provide a good surface finish and good dimensional accuracy with tolerances of ~10 µm and ~0.5 mm respectively. The mold consists of two halves made from a metal or a material having a melting temperature significantly higher than the molten metal. The mold cavity matches the design/geometry of the desired *iaito* plus the addition of injection and venting ports or channels. The mold cavity is coated with a refractory material to prevent the casting from sticking to the mold and to extend the mold’s life. The life of the mold is limited due to thermal fatigue and erosion. The mold evolves over its lifetime gradually impacting the geometry of the blade. When the life of a mold is exceeded it will no longer meet its tolerances and should be replaced. The mold design and the pouring/injection/drawing technique can introduce voids on the surface (scars, blisters, and scabs) and bubbles within the blade. One can hope, all such visibly flawed blanks will be discarded at this point.

Even under the best conditions molten alloys are susceptible to degradation [K2M, 2010]. I would assume Zn/Al alloys would have similar issues. Dissolved hydrogen may result in the formation of voids invisible to the naked eye. Oxidation reduces the effective cross section under load. Undesired trace compounds can form inclusions within the metal structure which will reduce fatigue performance. The rate at which a Zn/Al alloy cools (solidifies) will determine the blades dendritic/eutectic microstructures (grain size). Large grain size increases shrinkage, cracking, tearing and hydrogen porosity.



[Godec, 2013]

The above figure is the Eutectic phase diagram of Zn/Al alloys. Most of the property changes in a solid-liquid system are caused by the distortion of the crystalline lattice. The alloy composition and temperature of solidification can affect tensile strength, elongation, electrical resistivity, endurance, etc.

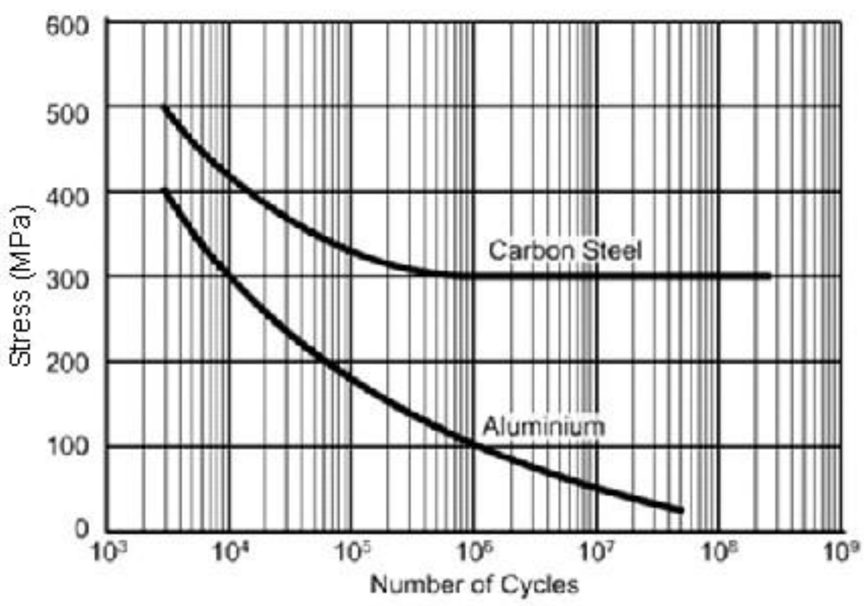
[Osorio, 2001]. [CET 2013] has been told that the slower the molten alloy hardens the better; the above figure supports this and illustrates that for a 92% Zn blade a particular crystalline lattice forms during the solidification at 419.5 degrees C.

After cooling, the blank will be removed from the mold. The excess material from the channels along with any flash will be removed and minor grinding, filing, and polishing is performed, as needed. The blank is then electroplated with copper and finally chrome plated. The *iaito's nakago* is then filed to accept the *habaki* and *tsuka*. The level of craftsmanship in this final shaping can create focal points for failure. Independent of the production are the properties of the Zn/Al alloy.

All metals and alloys have fatigue strength and some have a fatigue limit. In *Iaido*, the repetitive swinging and abrupt stopping of the blade places more stress on some parts of the blade than others. Specifically the *mune-mach, ha-machi and mekugi-ana* are the points of where a blade experiences the highest levels of stress. Let's look at some material data properties from the European Space Agency.

Fatigue limit and fatigue strength are terms used to describe the cyclic stress that can be applied to a material without causing failure. Cyclic stress in engineering refers to an internal distribution of forces (a stress) that changes over time in a repetitive fashion. Swinging a sword is an example of cyclic stress. Different materials respond differently to stress.

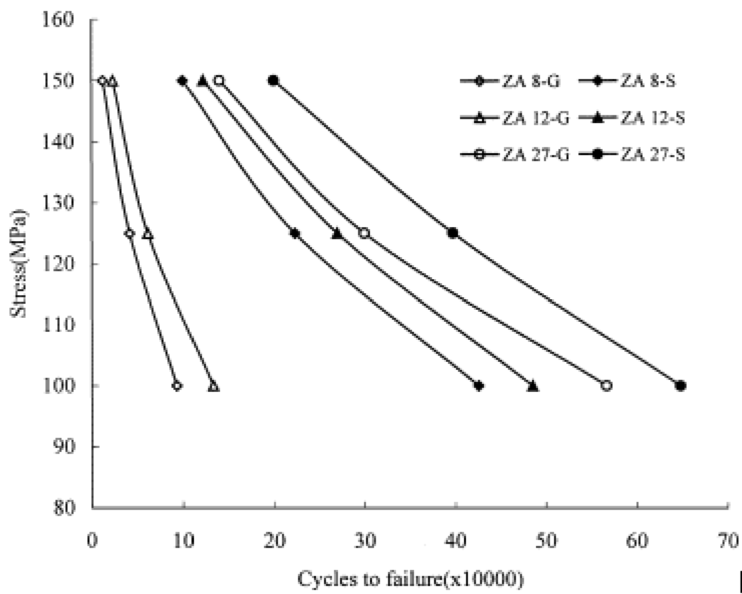
The figure below is a typical fatigue response curve of identical spacecraft components made from steel and aluminum. As the stress increases fewer stress cycles are needed to reach failure.



[ESA, 2013]

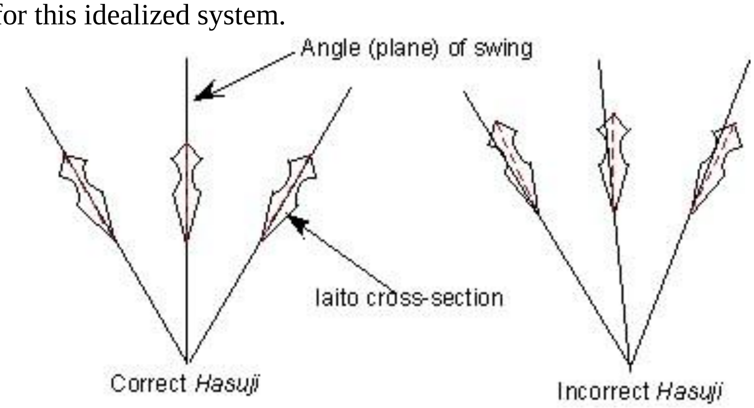
In the above graph, an aluminum component that is subjected to a stress of 200 MPa (1 MPa ~145 PSI) can be expected to fail after about 60,000 cycles. The steel component at this stress will never fail due to fatigue. Steel and titanium alloys have a 'fatigue limit' while most other metals such as aluminum, zinc, and copper have no fatigue limit and will eventually fail no matter what the peak cyclic stress is. Each alloy will have its own fatigue curve for a single cross section.

The Zn/Al alloy used in the fabrication of an *iaito* appears to be proprietary. Zn/Al alloys have high as-cast strength and relatively low melting temperatures. The mold life is longer for lower melting point metals. Common members of this group include ZA-8, ZA-12 and ZA-27, [EA, 2013]. The numbers (ZA#) represent the percentage of aluminum in the alloy. The remainder is almost all Zinc with trace elements of magnesium, copper, iron, lead, cadmium and tin. Zn/Al *iaitos* comply with the Japanese Firearms and Sword Law and are close in balance and weight of a *shinken*. As the percentage of aluminum increases the overall weight decreases. Steel (Fe), Zn and Al have densities of 7.874, 7.14 and 2.7 g/mL respectively. Based upon weight alone ZA-8 is probably close to the alloy used in an *iaito;* this assumption was later confirmed by analysis in the case study below. Below are the fatigue curves for three common Zn/Al alloys produced by gravity and squeeze casting.



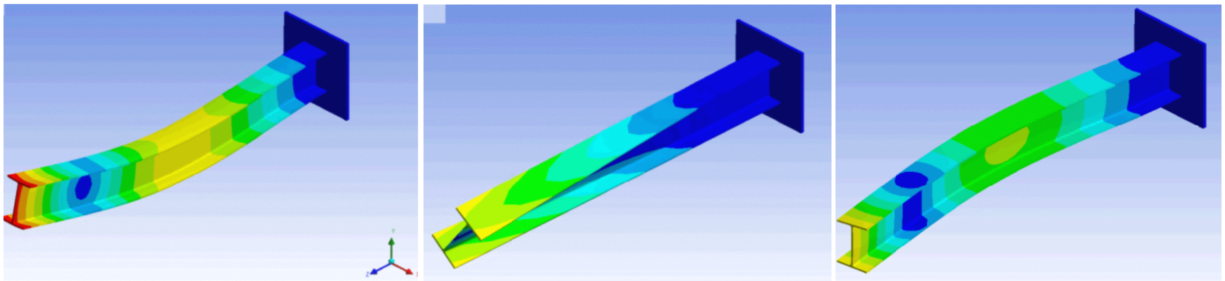
[EA, 2013].

What are the ramifications of improper *hasuji* on an *iaito*? There are three types of cyclic stresses that an *iaito* commonly experiences when swung, *i.e.*, vertical, torsional, and lateral. Focusing just on the forces of the swing, these terms are relative to the coordinate system of the sword and not the *iaido-ka*. In other words, correct *hasuji* (vertical stress) is present when the center line of the blade (line from the *ha-saki* to the *mune-suji*) lies on the plane defined by the arc of the *iaido-ka's* swing. This is independent of the angle of the swing, for this idealized system.



As mentioned earlier, one of the purposes of a *bo-hi* on a blade is to generate an audible *tachikaze*. It is a common belief that *tachikaze* is indicative of good *hasuji*. But it is easy to demonstrate that given enough velocity any object will make a noise as it moves through the air. Strong *iaido-kas* and beginners, often overpower the cut to achieve *tachikaze*. If their *hasuji* is not good, the *iaito* may be experiencing torsional and/or lateral bending which could damage it over time.

An *iaito* with a *bo-hi* can be thought of as a cantilevered I-beam. The figures below (Wikipedia, 2013) illustrate the primary bending modes (vertical, torsional, lateral) of a cantilevered I-beam.



For an I-beam, the maximum stress occurs at the fixed end; for an *iaito* that should be near where the blade meets the *tsuba*. This point experiences both tension and compression as it bends. Stress, *S*, is $S=M*c/I$, where *M* is the bending moment, *I* is the moment of inertia of the beam, and *c* is the distance from the centroid (center of gravity) to the fixed end. The bending moment is $M=P*L$, where *P* is the load (force) and *L* is the length from the fixed point. The fixed point will experience maximum stress when the load is at the free end of the beam. The moment of inertia, *I*, is dependent on the shape of the beam but the following usually holds: $I_{vertical} >> I_{lateral} >> I_{torsional}$. An *iaito* is optimally designed for vertical stresses (cutting). Torsional (twisting along the length of the blade) and lateral (bending perpendicular to the *shinogi-ji*) motions (improper *hasuji*) exert a relatively greater stress on the blade. Furthermore, as the blade length, *L*, increases, the moment arm increases and the stresses on the blade will increase. In other words, the longer the blade the higher the failure rate.

Consider a few rules of thumb regarding fatigue failures [ESA, 2013]:

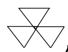
- The greater the stress per cycle, the shorter the time before failure.
- Fatigue tends to start at locations that have sharp internal corners (interfaces).
- The rougher the surface, the shorter the time before failure occurs.
- Damage is cumulative; materials do not 'heal' if rested.
- Time to failure is unpredictable.
- Damage is virtually undetectable unless you have access to specialized equipment, like X-ray, ultrasound, or UV fluorescent dye

Case Study

Recently (15Jun2013) the author's Zn/Al *iaito* failed catastrophically during Saturday morning *iaido* practice. It failed while practicing *Ipponme* from *Toyama Ryu Batto Jutsu*. The *iaito* was purchased in used condition before 1995. The blade length was 2-*shaku*, 5-*sun*, 5-*bu*, (~30"), and the sword weighed around 966 g. Upon inspection of the *nakago*, it was obvious that the blade was cast as the casting seam was visible. Initially it was believed that the *iaito's nakago* was glued into the *tsuka*, but this was not the case. The entire *tsuka/nakago/mekugi/*shim was just incredibly tight. The *tsuka-ito* was tight, the diamonds were regular, and the *same'* was actual ray skin. It was also interesting to note there were two tapered *mekugi-ana*, although only one was used. The third, middle hole was drilled and used as part of the copper electroplating and chroming process. This is visible in the picture below, looking at the *nakago*, you can see a chromed section followed by a copper section and terminating in the Zn/Al section.

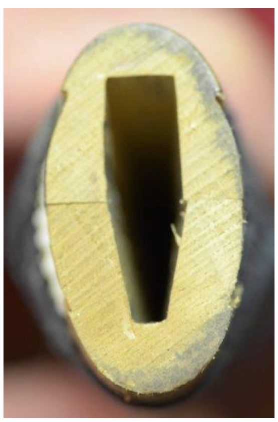
A simple binary analysis on the broken *nakago* revealed that the author's *iaito* had a mean density of 6.81 g/mL which corresponds to 92.47% Zn and 7.53% Al with a standard deviation of 2.67%. These results are very close to the assumed ZA-8 composition.

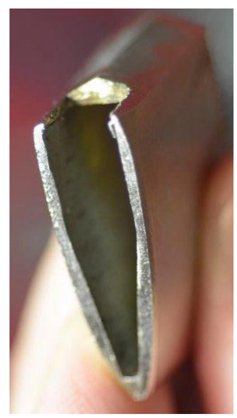
[Author's Broken Zn/Al *Iaito*, cast pre-1995]

The *nakago* has a faint stamp, , aft of the last *mekugi-ana* about 3 mm wide.

The blade failed at the *mune-machi* and a visible crack had started on the *ha-machi*. The gouges below the *bo-hi* were created when the *tsuba* was removed by the author.


The *kasane* of this iaito was 7.1 mm measured right below the *bo-hi* and the *mihaba* was 31.37 mm measured at the *ha-machi*. The metal grain sizes in the above photographs are typical, but there is a distinct color variation (lighter color) in the region of the *bo-hi*. There are no visible inclusions or flaws in the cast. The *ha-machi* and *mune-machi* are very coarse /rough and were probably made using a power grinder.





The *tsuka* opening looks perfect, and the *tsuka-ito* weave seems to match the *sageo*. The *habaki* was quite stout and was either silver-plated or stainless steel.

Conclusions

Referring back to the ESA rules of thumb:

- <u>The greater the stress, the shorter the time before failure</u>. The blade was probably over 20 years old. Beginning *iaido-ka* using incorrect technique (*e.g.,* inadvertently exerting torsional and/or lateral bending) may stress the blade more than an experienced practitioner. Most people practicing *iai* may never exert the stress /number of cycles required to fatigue the blade. But those who are strong and dedicated may experience blade failure.
- <u>Failure typically starts at locations that have sharp internal corners,</u> *i.e., ha-machi* and *mune-machi* notches. It looks like the upward cutting motion and reversal, as well as the downward cut and stop, had fatigued the author's blade.

- The rougher the surface, the shorter the time before failure occurs. The *ha-machi* and *mune-machi* surfaces were left in a rough filed condition. Is this level of finish normal?
- Damage is cumulative; materials do not 'heal' if rested. The *iaito* was probably 20+ years old with at least two different owners.
- Time to failure is unpredictable. No comprehensive analysis has been done to estimate the mean time before failure. This type of analysis is destructive by its very nature.
- Damage is undetectable unless you have access to specialized equipment. Fatigue begins as micro-cracks which are only detectible using expensive X-ray and or ultrasound equipment. If cracks are visible on the blade originating at the *ha-machi* or *mune-machi* notches, **stop** using the *iaito* immediately and get another one!

When practicing *Iaido*, always be aware of where others are located in your general vicinity. Swords are potentially dangerous. Always remain respectful of the harm that can come from familiar tools and familiar activities. This should go through your mind when you bow to your sword at the beginning of every class. When purchasing a sword talk with someone knowledgeable, at the very least your *Sensei*. Their advice and experience are invaluable. Used swords are like used cars, and you never know what has been done to them. Don't over-power a cut, and understand where the cut begins and truly ends. Finally, you need to refine the technique slowly before adding power and speed. You've got to go slow to go fast!

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Glossary

bo-hi – groove
bu – Japanese unit of measure (3.03 mm)
dan – an advanced proficiency level in a Japanese martial art 1-10
habaki -- blade collar
ha-machi -- edge notch
hamon -- temper pattern
hasuji – improper cutting line with respect to the geometry of the sword.
ha-saki – cutting edge of blade
Iaido -- is the Japanese way of drawing and cutting with a sword
iaido-ka – *Iaido* practioner
Ipponme – first kata
kasane – thickness of the blade
kesa-giri -- downward diagonal cut
kirioshi -- downward vertical cut
kizu – scratches or flaws in the metal of the blade
kyu – a beginning proficiency level in a Japanese martial art 10-1
mekugi – peg that goes through tsuka and nakago
mekugi-ana -- holes in the nakago
mihaba – width of the blade
mune-machi -- back notch
mune-suji – back edge of the blade
nakago -- tang
sageo -- saya cord
same' -- handle covering
saya – sword scabbard
Sensei -- teacher
shaku – Japanese unit of measure (30.3 cm)
shinogi-ji -- flat of the blade
shinsakuto – newly made swords
sun – Japanese unit of measure (3.03 cm)
tachikaze – (sword-wind) the swoosh or whistle as the sword cuts the air.
tameshigiri – test cutting.
Toyama Ryu Batto Jutsu – a style of *Iaido*
tsuba -- sword guard.
tsuka -- handle
tsuka-ito -- handle wrapping

風柳　剣人 (Kent Krumvieda)

Kent has been practicing *Muso Shinden Ryu* and *Toyama Ryu Iaido* at the *Tanshinjuku* Boulder Colorado dojo under Steven Shaw *Sensei* <http://www.iaidotsj.org/> since 2008. Kent has a B.S. in chemical engineering, a M.S. in civil engineering and has taken course work towards a PhD in aerospace engineering. He has no formal training in metallurgy, and is not an expert on the fabrication of Zn/Al *iaitos*. All information contained in this paper was obtained from publically available sources.