

Material selection for climbing hardware using the example of a belay device

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Abstract. The aim of the research project was to design a novel climbing belay device. The present article describes the details of the therefor performed material selection. Literature research on the materials used in commercially available belay devices revealed a lack of definite information. Thus, a pilot x-ray fluorescence (XRF) test was performed on a small sample of common aluminium belay devices. It revealed the use of a variety of different alloy systems. The selection process continued by compiling a thorough list of constraints and objectives for this safety related piece of sports equipment. Different material options including non-aluminium-materials were discussed. The final material choice was a high strength aluminium alloy with a T6 thermal treatment. The device was designed and calculated by use of CAD and FEM software respectively, aiming to reduce weight. After manufacturing the strength, usability and friction properties of the device have been successfully tested.

1. Introduction

Belay devices are manually operated rope brakes, a central element of climbing safety equipment. Their function is to introduce a braking force to the “life” rope in order to stop a leader fall or allow a controlled rappel. The rope glides through the device against the generated braking force transforming the kinetic energy of the falling climber into thermal energy. The fall comes to a halt as soon as the kinetic energy is fully dissipated. In the process life rope forces can reach values of several kN [1], requiring the belay device to withstand them. This paper describes the process of material selection for a newly developed manual belay device (see figure 1). The main purpose of this particular device is belaying a lead climber directly off the anchor in a multi pitch scenario. It has been designed in accordance to the DIN EN 15151-2:2012 standard.



Figure 1. The developed belay device attached to an HMS carabiner and rigged with a climbing rope. The “control” rope can be seen at the bottom and the “life” rope at the top of the image. The control rope force introduced by the operator’s hand is amplified by the device, allowing the control of the life rope force.



1. Industrial manufacturing and materials

Due to growing popularity of the sport, mountaineering equipment has become very sophisticated. A part of the development is a growing range of materials in use. Belay devices have traditionally been cast or wrought from aluminium alloys [2]. Typically only this single material was used for the whole device. Modern devices often incorporate a variety of different materials, especially if moving parts are involved. These are most common in belay devices with assisted locking and are typically mounted on steel axles (Grigri by Petzl) and rarely on brass slide bearings (Sirius by Tre, see figure 2). Also, some devices consist of punched sheet metal parts that are held together by steel rivets (Smart by Mammut). Tube-type devices commonly have a retaining steel-wire-sling with a polymer coating. For better ergonomics non-load-bearing polymer parts are incorporated in modern devices (Ergo by Salewa). Yet aluminium alloys remain the most common load bearing material followed by steel, investment cast stainless steel in the case of the Megajul by Edelrid. Even this latter material description is uncommonly precise for an advertisement of climbing equipment. The manufacturers clearly attempt to keep their secrets.



Figure 2. Brass inserts as sliding bearings on a moving component of the Sirius belay device by Tre.

1.1 Literature research

Unfortunately, the scarce information provided by the manufacturers is only marginally supplemented by literature. Blackford [2] merely states that belay devices are made from high strength aluminium alloys, but does not specify further details, even though she provides more precise material information on other types of mountaineering hardware. Two later articles by Fuss and Niegl [3, 4] which deal quite deeply with the matter of belay devices completely ignore the material aspect of the problem. Titt provides interesting ideas in an article on the website of his employer, a mid tier rock anchor manufacturer [5]. In particular it raises awareness of the importance of thermal conductivity to the soundness of the climbing rope. Even though the article does not conform to scientific standards, it has been an important source of inspiration, and therefore deserves credit.

1.2 Pilot x-ray fluorescence test

The lack of information on the alloys in use led to the testing of three different belay devices via x-ray fluorescence analysis (XRF). XRF analysis cannot reveal the exact composition of aluminium alloys due to its low atomic number. While alloying elements can be detected, the aluminium itself remains invisible, thus giving no reference for a calculation of alloying element percentages. Still, by displaying the engaged alloying elements, the method can give an insight on the chosen alloy systems. These in turn allow assumptions about an eventual heat treatment of the devices. The results of the analysis are summarized in table 1. All three devices show the presence of manganese, which is the only alloying element in the Sirius, proving it to be made of a non-heat-treatable 3xxx-series alloy. The other two devices additionally show the presence of copper, one of them also containing zinc, which indicates 2xxx- or 7xxx-series alloys, respectively. All this shows that no consensus on a material choice for belay devices has been found yet among the manufacturers. Even heat treatable alloys are not a standard choice despite their superior structural properties.

Table 1. Alloying elements detected via XRF analysis and possible conclusions.

Belay device	Manufacturer	Alloying elements	Possible alloy series			Impurities
Bat Brake	Edelrid	Mn Cu	3xxx	2xxx		Fe
ATC Guide	Black Diamond	Mn Cu Zn	3xxx	2xxx	7xxx	
Sirius	TRE	Mn	3xxx			Fe
			non-heat-treatable	heat-treatable		

1.3 Assumptions on manufacturing techniques

By examining manufacturing traces on the surface of commercially available climbing equipment, an attempt is made to identify the manufacturing methods of the above-mentioned devices. The Sirius and the Bat Brake were presumably drop forged. They exhibit an appropriate geometry for this forming process and feature circumferential burrs, which indicate a removal of the excess material by stamping (see figure 3). The manufacturing method of the ATC cannot be determined as easily. It has no obvious traces of stamping or similar procedures and a more complex geometry than the Bat Brake or the Sirius. Several undercuts indicate that the ATC might be investment cast similar to the Magajul.



Figure 3. Burrs on the edges of the Bat Brake by Edelrid, where the excess material from drop forging was presumably removed by stamping.

1.4 Conclusion

There is only little to no information on the exact alloys, manufacturing techniques and heat treatment of commercially available belay devices. It is clear that the material class of aluminium alloys is the most popular, being the choice of most manufacturers. Stainless steel is the second, far less popular choice. No other materials are being used as base material for belay devices at the present.

2. Material selection

After the foregoing insight into the material choices in the industry, an own independent effort to systematically select a material is made. In the following, general design requirements for belay devices are rephrased into unique constraints and objectives. The latter are then used to systematically sort out inappropriate material families and classes and single materials leaving behind the most appropriate material choice.

2.1 Design requirements

From the functions a belay device performs, the obstacles it meets and the environmental influences it endures the following requirements are derived:

- Climbing safety equipment is supposed to ensure safety without compromising the mobility of the climber. Thus **low weight at a sufficient breaking strength** is a major requirement.
- For the sake of sustainability the device **should last as long as possible**.
- Obviously, the device **should not damage the rope**.

2.1.1 Constraints

- The devices are often being used outdoors in bad weather or at the sea side. Thus **sufficient corrosion resistance** is required for longevity.
- **No rope damaging features should be contained within the material.** Their exposure by abrasion or corrosion, no matter how slow, could damage the rope.
- The **melting temperature** of the material should not be reached, as this would damage the rope.
- The material **should be affordable and available.**
- A **sufficient size of pre-product** is required to meet the dimensions of the future device.

2.1.2 Objectives

- **Maximize weight specific yield strength** for low weight at sufficient strength!
- **Maximize abrasion and wear resistance** for longevity!
- A belay device in outdoor use will often have contact to the rock surface, occasionally this will also occur under considerable loads. Experience shows that belay devices accumulate grooves and indentations on their outer surface over the years of use. This superficial damage can lead to high stress concentrations and eventually to failure. Sufficient toughness is required, to reduce and withstand local stress concentrations. Unfortunately a thorough series of tests would be necessary to define the exact level of toughness needed. Without this knowledge it is expedient to **maximise toughness**. This only makes sense within the limits of the previous two objectives, since toughness and strength are interdependent and cannot be raised in equal measure.
- In case of a deep fall (say 10 m), when a large percentage of the energy must be absorbed by friction inside the belay device (factor-2-fall), an 80-kg-climber and an assumed braking duration of 1 s the average heat flow rate to be dissipated almost reaches approximately 8 kW. Due to the low melting temperature of the rope material (typically PA 6.6) and its potential damage, high temperatures and thus the accumulation of thermal energy is to be avoided. To make this possible **thermal conductivity should be maximized**. As in the previous point, for future projects it would make sense to determine a minimum level of thermal conductivity and capacity to ensure safety.

2.2 Choice of material family

The material families taken into consideration are ceramics, composites, polymers and metals. Ceramics are too brittle and would not only suffer from stress concentrations at superficial indentations, they could also be damaged if dropped from a height. Composites contain fibres that might be exposed by abrasion. Especially glass or metal fibres might damage the rope if exposed. Composites with a polymer matrix feature the same downsides as the polymers themselves: low thermal conductivity [6], low melting temperature (for thermoplastic polymers) and low abrasive resistance. Only metals meet all requirements mentioned above, thus qualifying for the next selection cycle.

2.3 Choice of material class

The material classes taken into consideration are high strength steels, stainless steels, magnesium alloys, titanium alloys and aluminium alloys. High strength steels and magnesium alloys drop out due to their typically low corrosion resistance, which makes them impractical in the outdoors. Titanium alloys and stainless steels exhibit a very low thermal conductivity compared to aluminium (see figure 4), which might lead to overheating and rope damage. By the method of elimination the aluminium alloys remain to be the only acceptable material class. It is important to note that aluminium is chosen over stainless steel just as high thermal conductivity is chosen over wear resistance for a reason: the first influences the safety of the device, while the second only prolongs the life span. Picking safety over life span is an easy choice.

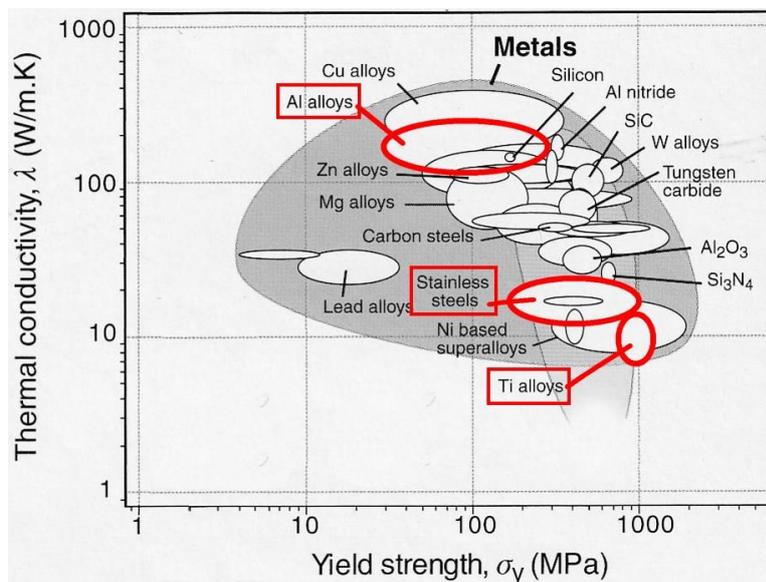


Figure 4. Material property chart of yield strength vs. thermal conductivity, an extract from [6, p. 252].

2.4 Choice of single material

To make a choice within the material class of aluminium alloys it is expedient to check which ones of the constraints and objectives remain unfulfilled and can be influenced by the imminent choice. Three remaining goals result from this: to maximize weight specific yield strength, to maximize abrasion and wear resistance and to ensure sufficient toughness.

The overall wear resistance of aluminium alloys is relatively low. It increases with rising hardness and yield strength, but this is only one of the influencing parameters [6]. The presence of above-average hard grains in a relatively soft surrounding grain structure can lead to considerable elevation of wear resistance [7], without necessarily changing the macroscopic hardness. At the same time such grains or precipitates could lead to a faster abrasion of the rope, thus conflicting with one of the above formulated constraints: No rope damaging features should be contained within the material. Another issue is the continuous formation of an oxide layer on the surface of aluminium alloys and the option of anodising the surface intentionally, both having a yet unpredictable effect on wear behaviour in combination with a textile surface. Due to all these difficulties only the positive effect of increasing yield strength shall henceforth be taken into account for wear resistance. This agrees with the objective to maximise the weight specific yield strength. The densities of the different alloys are fairly similar, so the alloy with the highest yield strength can be chosen. Also this simple approach doesn't seem to affect the toughness strongly [6], which makes it acceptable within the formulated objectives. Thus the strongest accessible aluminium alloy is chosen: EN AW-7075.

2.5 Material treatment

The T6-heat-treatment has been applied, the resulting material being EN AW-7075-T6. The treatment involves three steps: dissolving the alloying elements in the solid aluminium at high temperatures; quenching to provoke supersaturation at low temperatures; and aging at medium temperatures to receive finely dispersed precipitates that maximise yield strength.

3. Further development

3.1 Construction

The conception of the created belay device was structured according to the VDI 2221 guideline. Handling, rope friction and strength were taken into account. The belay device was modelled with CREO Parametric (Parametric Technology GmbH, Unterschleißheim, Germany). The effects of the 7 kN force on the life rope required by the DIN EN 15151-2 standard were simulated via CREO

Simulate and the bolted joint additionally calculated according to the VDI 2230 guideline. The geometry was iteratively altered to save weight and to meet the required safety margins according to the FKM-guideline. The braking force generated by the device was adjusted to match that of the ATC (a popular tube-type device) and the Munter hitch, being two widely accepted references.

3.2 Manufacturing

The belay device prototype has been CNC-milled and hand-finished. The two symmetrical halves were bolted together using a torque wrench. The elongation of the bolts was controlled with a micrometer to meet the required pretension.

3.3 Testing

Usability, rope friction and strength of the prototype were tested. The usability was tested with volunteers in a safe environment. The resulting belay device has minor usability issues but has otherwise proven to be fit for use. The rope friction test involved a mechanical (“simulated”) hand that substituted the force of the operator’s hand. The friction generated by the device meets expectations. Being the only material-related test the strength test is described below. The test was performed in accordance to the requirements of the DIN EN 15151-2 standard (see figure 5). The device was connected to the lower attachment point of a tension testing machine with a climbing carabiner as it would be in the intended application. The “life” rope was connected to the upper attachment point while the “control” rope was directed to an additional attachment point at a 30° angle from the pulling axis. The arrangement was then loaded with 7 kN life rope force. The device withstood the applied forces without major deformations. The only plastic deformation was an indentation of the contact area between the attachment carabiner and the device body. This indentation being a typical deformation with most belay devices and being located in an area of compressive stress is considered harmless. Hence the device passed the test.



Figure 5. The belay device as it was tensioned during the pull test: The device attached to the tension testing machine with a carabiner, the life rope going upward and the control rope leaving the device at an angle of 30°.

4. Conclusion

Though the systematic approach towards a material choice for a climbing belay device results in the selection of a very typical material, the high strength aluminium alloy EN AW-7075, it shows that some constraints and objectives need a more precise formulation. The call for toughness, wear resistance and thermal conductivity is clearly motivated but not properly quantified. This results in the inefficient maximisation of quantities, that most probably only need to exceed a discrete value. Defining these values should be the topic of future studies.

For the present project the material selection depicted above has been a success. A prototype has been built from the chosen material and its functionality and strength have been successfully tested.

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References

- [1] Blackford J R 2003 Materials in mountaineering *Materials in sports equipment* ed M Jenkins (Boca Raton, Cambridge: CRC Press) chapter 11 pp 279–325
- [2] Semmel C 2002 Die Handbremse *DAV Panorama* **4** 61–3
- [3] Fuss F K and Niegl G 2010 Design and mechanics of belay devices and rope brakes *Sports Technology* **3** 68–87
- [4] Fuss F K and Niegl G 2014 Design and mechanics of mountaineering equipment *Routledge handbook of sports technology and engineering* ed F K Fuss, A Subic, M Strangwood and R Metha (London: Routledge) chapter 17 pp 277–92
- [5] Titt J 2009 Belay Device Theory, Testing and Practice *online* 22 august 2016
<http://www.bolt-products.com/Glue-inBoltDesign.htm>
- [6] Ashby M, Shercliff H and Cebon D 2008 *Materials. Engineering, science, processing and design*. (Amsterdam: Elsevier)
- [7] Drossel G and Kammer C 2010 *Aluminium-Taschenbuch* (Duesseldorf: Aluminium-Verlag)