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Concerning the Sharpness of Blades

A high level of sharpness of cutting tools is preferable, just as it is for edged weapons. While tools are generally used in well defined situations for which they are optimised, edged weapons, particularly those with longer blades, have to meet conflicting requirements. Within the scope of this work, influences on the sharpness of blades and their further effects as well as the necessary design trade-offs are evaluated.

1 Factors of Sharpness

While sharpness is an everyday concept, there is no uniform definition. It would, however, stand to reason to regard a blade as sharper, the less force it requires to cut a certain material or the deeper the cut becomes with a given force. Concurrently, the blade should not only be sharp, but should also retain its edge, i. e. the edge should withstand many cutting processes without a significant decrease in sharpness. Moreover, it is preferable to use a blade that withstands stress not only from ideal cutting processes – particularly when fencing. Depending on the respective application, an optimum compromise of sharpness and robustness has to be found. [1, 2]

Several factors determine the sharpness of a blade, among them the properties of the steel, the relative motion of blade and target, the curvature of the blade, the edge angle, grinding and finish.

1.1 Edge Radius and Finish

McCarthy et al. [3] determined the dependence of the force F required for cut formation on the finite edge radius r and found a proportional relation:

$$F \propto r \tag{1}$$

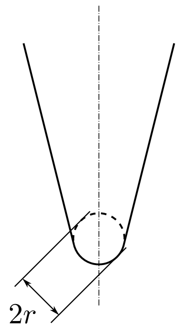

Figure 1: Edge diameter $2r$

As cutting edge area is proportional to cutting edge radius r, this result is in agreement with the proportional relation of force and cutting edge area found by Szabo et al. [4]. The edge radius r, see Fig. 1, typically is in the low µm range. Hence, this factor of sharpness is generally not visible to the naked eye.

The finish of the edge contributes to the sharpness of the blade in two ways. For one thing, a finer finish of the cutting surfaces yields a finer edge with a smaller edge radius r and fewer defects. For another thing, a finer finish results in a smoother surface of the edge, thus reducing cutting friction. This effect is also achieved with coatings such as amorphous carbon on e. g. razor blades. [2] It should be considered, though, that only friction at the very edge substantially contributes to the total frictional resistance for most substrates. However, the edge is where a coating would be quickly removed upon re-sharpening. McGorry et al. [5] analysed the effect of blade finish on the applied force during different lamb meatpacking operations. While a finer blade finish reduces the required force for elongated cuts through different tissues significantly, the finish has a similar effect for shorter cuts through muscle only as a tendency, but the effect was below level of significance. Landes [2] explains that saw-like burrs on the edge might assist cutting operations which include a distinct slicing component, such that the influence of blade finish might vary with the execution of the cut.

1.2 Edge Angle, Single and Double-Edged Blades

The edge angle is the angle at which the surfaces of the edge or their respective tangent planes intersect. Marsot et al. [1] assessed the force F required for a boning knife to cut a meat-like substrate under laboratory conditions with edge angles ε of 27°, 30°, 35° and 40°. They concluded that the force F is proportional to the tangent of half the edge angle:

$$F \propto \tan\frac{\varepsilon}{2} \tag{2}$$

Arcona und Dow [6] found the same correlation for the slitting of plastic films using edge angles smaller than 45°. McCarthy et al. [3] used finite element method to model a cutting process and suggested a bilinear relation between the force F that forms a cut in polyurethane substrate and the edge angle ε. However, also Eq. (2) adequately describes their results, see Fig. 3. Marsot et al. [1] not only assessed the impact of the edge angle and the steel grade on the sharpness, but also on cutting edge retention and arrive at the plausible conclusion that an obtuser angle yields higher cutting edge retention.

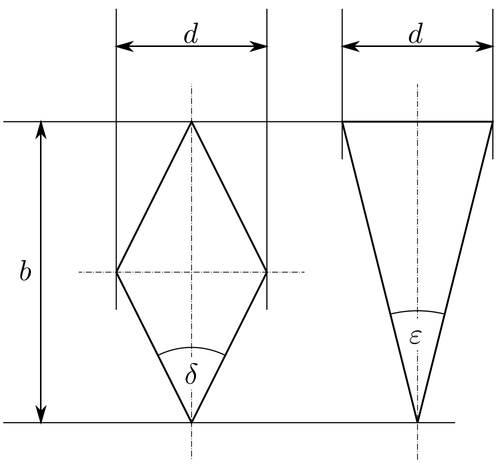

Figure 2: Width b, thickness d and the edge angles δ and ε, resp., in a rhombic and a triangular blade cross-section

McGorry et al. [5] evaluated under field conditions the effect of the edge angles 20°, 30° and 45° on the force required for cutting meat. They deduce from their measurements that within the evaluated range of angles, the edge angle does not affect the required force significantly. This suggests that the sharpness reducing effect of larger edge angles is in practice overlaid with other effects. McCarthy et al. [3] consider the edge angle less important than other effects.

A double-edged blade with rhombic cross-section has larger edge angles than a single-edged blade with the same blade width, thickness and cross-section area with a triangular cross-section, as it is shown in Fig. 2 for blades without chamfers or fillets (convex or hollow grind). Basic geometric considerations neglecting the exact grinding yield the relations for the edge angle δ of a double-edged blade with rhombic cross-section, the edge angle ε of a single-edged blade with triangular cross-section, the blade thickness d and the blade width b:

$$\tan\frac{\delta}{2} = \frac{d}{b} \tag{3}$$

$$\tan\frac{\varepsilon}{2} = \frac{d}{2b} \tag{4}$$

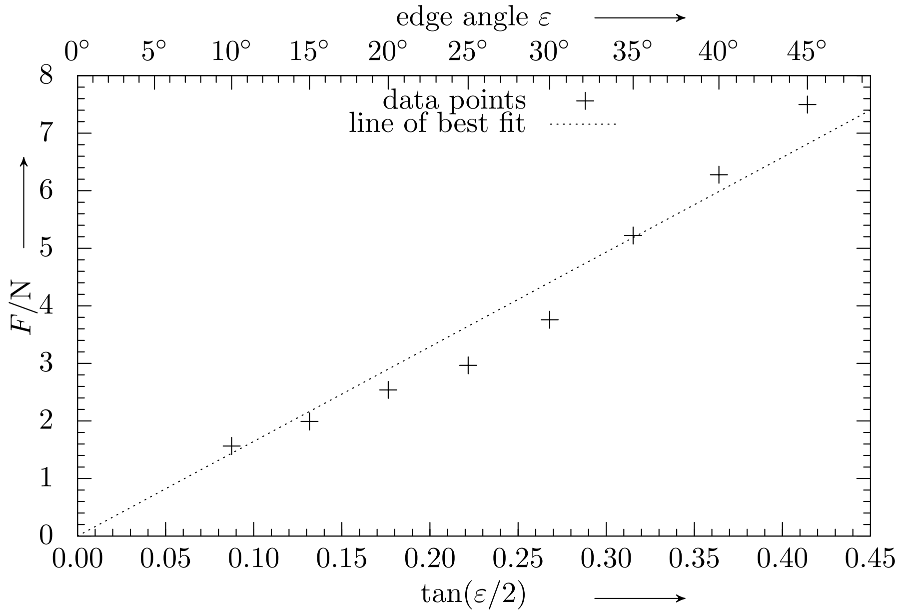

Figure 3: Relation of F and $\tan(\varepsilon/2)$ with line of best fit through origin, data points taken from [3]

For the ratio of the edge angles δ and ε, this results in:

$$\frac{\delta}{\varepsilon} = \frac{\arctan(d/b)}{\arctan(d/2b)} \tag{5}$$

For the limit cases, i. e. a blade with square cross-section with $b = d$ and for blades with a slim profile, i. e. $b \gg d$, the boundary values of δ/ε are:

$$\left.\frac{\delta}{\varepsilon}\right|_{b/d=1} \approx 1.69 \tag{6}$$

$$\lim_{b/d\to\infty} (\delta/\varepsilon) = 2 \tag{7}$$

Equations (6) and (7) as well as Fig. 4 show that the same ratio of blade width and thickness yields an edge angle δ of a double-edged blade with rhombic cross-section which is 1.69 to 2 times as large as the edge angle ε of a single-edged blade with triangular cross-section. From Eq. (2) follows that the cutting force of a double-edged blade needs to be twice as large as for a single-edged blade with the same ratio of width and thickness.

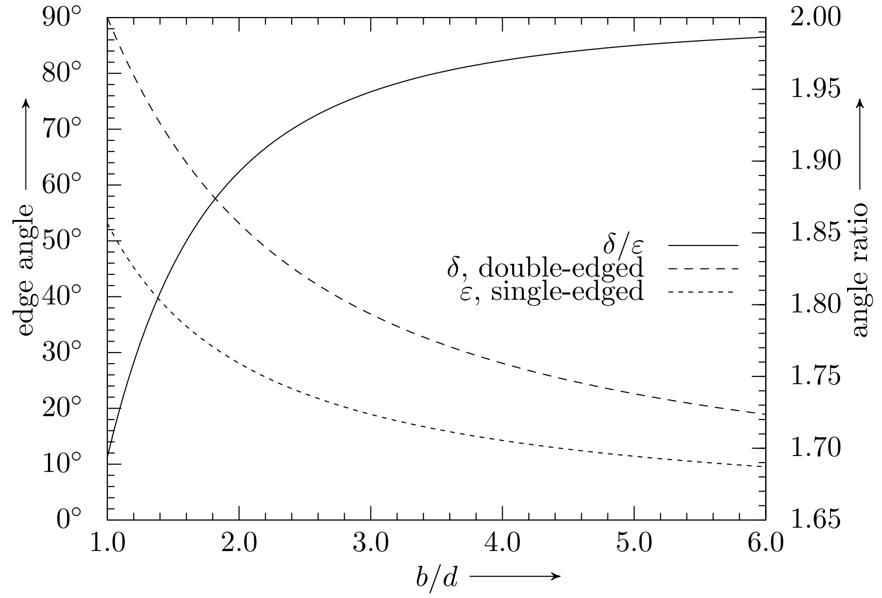

Figure 4: Edge angles δ and ε and their ratio $\frac{\delta}{\varepsilon}$ plotted against the ratio of blade width b and blade thickness d

1.3 Steel Grade

Marsot et al. [1] compared blades with identical geometric properties but different alloys and hardnesses. They used boning knives made from X46Cr13 steel with a hardness of 54(1) HRC, from X50CrMoV15 with 56(1) HRC and from X70CrMo15 with 57(1) HRC. The steel grade had no effect on the initially required cutting force. Yet, the required cutting force increased less for harder steel grades.

However, it should be considered that Marsot et al. assayed only stainless steels which are not suitable for sword blades because of their low toughness. Landes [2] explains that the feasibility of some edge geometries depend on the steel. Thus, brittle steels with higher concentrations of large carbide phases cannot form edges with small edge radii r, as a thin edge would break upon grinding. This results in a larger minimum width of the edge. Smaller edge radii can only be achieved with more ductile steels.

The steel and its heat treatment not only affect the edge of a blade, but also other properties which are relevant in fencing. Thus, an overly hard and brittle blade blade yields a lower impact resistance, i. e. a higher risk of fracture. The higher risk of fracture can be compensated with a thicker blade, which would in turn change the mass and mass distribution. While a higher brittleness or an altered mass distribution would have a smaller impact on shorter blades, longer blades such as the longsword's would become brittle or inertial beyond usability.

1.4 Slicing Component and Blade Curvature

Atkins [7] analysed the effect of blade curvature on the force required for cutting soft materials. He explains that the blade curvature affects the cutting force through the ratio ξ of the blade velocity component along the edge (slice) and the blade velocity component perpendicular to the edge (push). In general, a larger slice/push ratio ξ decreases the force perpendicular to the blade independently of the microscopic properties of the blade. This not only reduces the required force, but also increases the quality of the cut, e. g. when cutting foods or during microtomy. Tangential velocity, however, is practically bounded above [7, 8], particularly during manual blade operations such as fencing. Besides blade curvature and velocities of blade and target, the slice/push ratio ξ also depends on the angle between edge and target surface. Apart from adapting the blade curvature to a certain motion, it is also possible to adapt the motion to a given curvature. [7]

Landes [2] considers the slice/push ratio ξ qualitatively and geometrically explains the reduced force effort with a smaller effective edge angle ε_{eff}. In his depiction, the effective edge angle ε_{eff} results from a projection of the edge angle ε into a plane perpendicular to the plane of cutting and parallel to the cutting direction. Thus, the effective edge angle ε_{eff} is:

$$\frac{\tan(\varepsilon_{\text{eff}}/2)}{\tan(\varepsilon/2)} = \left(1+\xi^2\right)^{-\frac{1}{2}} \tag{8}$$

Using Eq. (2), this gives the effective required force F_{eff}:

$$\frac{F_{\text{eff}}}{F} = \left(1+\xi^2\right)^{-\frac{1}{2}} \tag{9}$$

Atkins et al. [8] arrive at the same conclusion when friction is neglected. In Fig. 5, the required force is plotted against ξ.

2 Conclusion

Several properties of a blade define its sharpness. The steel and its heat treatment allow edges of different acuteness and determine the range of reasonable edge angles. For the use as a sword blade, it should be considered that the steel should be sufficiently tough to resist contact with hard targets. Also, the edge angle must be large enough to avoid fast wear in typical fight situations. The necessarily ductile steel of a contact ready sword allows grinding of small cutting edge areas. A small cutting edge area is more important for the sharpness of a blade than an acute edge angle. [1, 3, 5]

Besides the properties of the blade itself, its manipulation also affects its sharpness. The motion of the blade, its declination and its curvature result in the slice/push ratio ξ. In general, a larger slice/push ratio ξ reduces the force required for a cut. [8] However, there are practical limitations for the slicing component of manually operated blades as well as for the curvature of blades used in combat situations. [7]

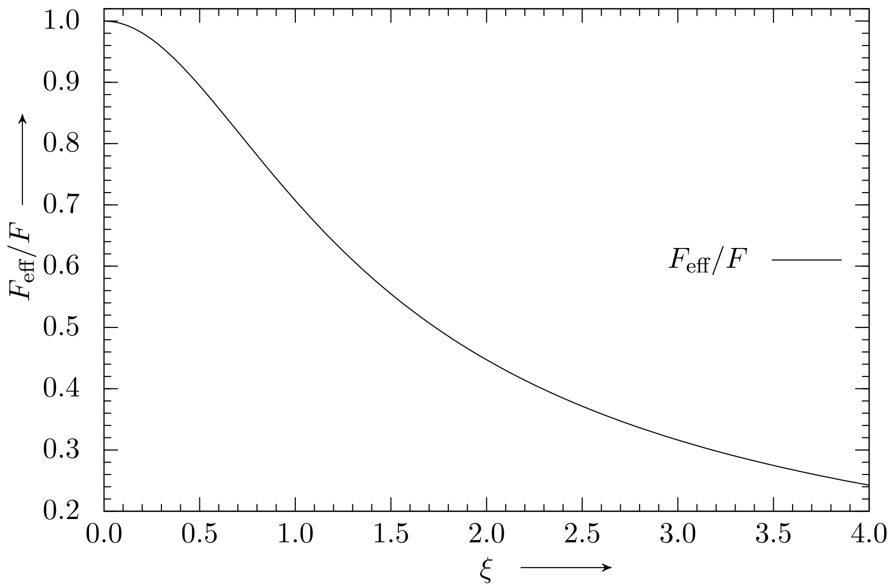

Figure 5: Decrease in the force required for a cut plotted against the slice/push ratio ξ, friction neglected

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