A Brief Review of Gemstone Optical Properties From a Lapidary's Perspective

Sandrine Kunz July 2000

Contents

1 Introduction

1.1 Importance of the Lapidary Process

With the exception of pearls, almost all gems need enhancement by shaping, faceting or polishing. Rough gemstones, with the exception of their crystal shape occurrence, are not very attractive when extracted from the mine. Therefore, different techniques are available to emphasise their appearance depending on the quality and the type of mineral.

With translucent or opaque stones the usual cutting style may be the rounded cabochon form, which brings out their phenomena[1] or simply their body colours. Other techniques for enhancing appearance such as tumbling, carving or engraving exist, but are not commonly used in jewellery.

Most transparent minerals are faceted to enhance features such as colour, brilliance, fire and scintillation. Because the light can travel within the stone, the analysis of the optical properties is critical. This is for this reason that the main purpose of this paper will focus on the optical properties of transparent gemstone cut by the faceting technique. As well, the inclusions affecting the clarity and their issues during faceting will not be discussed.

1.2 Faceting Technique

The main goal of faceting is to get the highest yield from the rough, in order to produce the most beautiful gem with the highest value and the maximum weight. The cutting involves four steps:

I. Sawing (sometimes omitted with small or well shape roughs)
II. Preforming (shaping and orientation)
III. Facet grinding
IV. Polishing

The faceting of diamonds is very specific due to their optical properties, hardness, directional hardness and cleavage properties. Several books, such as *Diamond Cutting* by Basil Watermeyer, deal specifically with diamonds, but it is beyond the scope of this paper to do so. Reference to diamonds will be made only to illustrate general concepts.

[1] Phenomena is an optical effect in visible light occurring in certain, but not all specimens of a species. (For example, chatoyancy, asterism, play of colour ...).

Initially, the rough is carefully analysed to determine how it can be best utilised. The first two steps, sawing and preforming, are the most important because they dictate the shape and influence the final weight. This procedure is critical to the faceting process, as the final decision fixes the orientation of the rough, the shape and the proportion.

During the orientation of the rough, not only the optical properties are cautiously reviewed but the other properties are also of great importance. Twinning lines, directional hardness or cleavage, are critical later in the cutting and the polishing process and should therefore also be assessed during the orientation stage.

Compared to preforming, faceting and polishing are relatively simple tasks. The cutter will choose a cutting style (step-cut, brilliant or mix-cut) based upon the type of gem material, in order to improve the body colour of the gem or create more brilliance. The brilliant cuts are best for brilliance whereas step cuts are known to enhance the colour. The cut is also chosen as a function of the optical properties, so let us review them from a lapidary's perspective.

2 Optical Properties

2.1 Introduction

The optical properties are of great importance when cutting a transparent rough as the light give life to the gem. Without an understanding of how light travels in a stone or how colour is produced, the resulting faceted gemstone could have poor colour, no brilliance or a "fish-eye"[2].

2.2 Colour

Colour is the most important characteristic of gems. Gemstones are coloured by the light, thanks to their ability to absorb one colour from the six that comprise white light: red, orange, yellow, green, blue, or violet. If the stone absorbs no colour, it will appear colourless. If all the colours are absorbed, the stone will be black. If green is absorbed into the stone, the stone will show the complementary colour to the one absorbed, in this case red.

What is important for the lapidary to consider is that the distance the light ray travels through the stone can influence the absorption and thus the colour. For example, in light minerals, a deep pavilion can deepen the colour of the outgoing light. Light, travelling this longer path, takes on a deeper hue as it is subject to much more colour absorption.

Dark gemstones are more complex and other optical properties are involved. These issues are discussed later, under chapter 2.8.

The influence the lapidary can have on colour, is necessarily limited to the quality of the mineral. The examination of the colour distribution and its quality is performed during the purchase of the rough. A good choice at this stage will reduce greatly the challenge of handling the colour, and challenges presented by the other optical properties.

[2] See explanations in paragraph on Refractive Index 2.3.

2.3 **Refractive Index**

The refractive index (RI) is of prime importance to the faceter. When the light passes from air to another medium like a gemstone, the light path is modified because the velocity of light is lowered in the denser medium. In other words, the light is refracted. The amount of refraction is called the RI and is defined as: the ratio of the velocity of light in air to the velocity of light in the gemstone.

Another term commonly used in cutting is critical angle (CA). Within this angle[3], the incident light ceases to be reflected on a surface of the stone (reflection at points 2 in figure I) and the light will enter the stone to be refracted (refraction at point 1&3 in figure I and at point 1&2 in figure II). The critical angle is inversely related to the RI. This means that the higher the RI, the smaller the critical angle. This can be seen in that for maximum brilliance, the pavilion/girdle angle for a quartz gemstone (RI 1.54 ; CA 40.33^{o}) will be significantly different from that for a diamond (RI 2.42 ; CA 24.43^{o}).

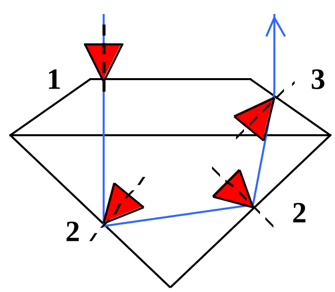

Fig. I Illustration of the critical angle, in red, and total internal reflection

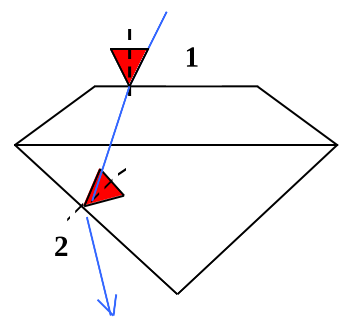

Fig. II light, in blue, is refracted out of the pavilion as the angle is less than the critical angle.

Total internal reflection is also a term in relation with RI and the critical angle. Total internal reflection is the ability of a faceted stone to: (1) refract the incident light, (2) reflect the light from the lower pavilion facets, and (3) refract the light from the crown facets (see Figure I). This is the main objective of the lapidary as he or she must adjust the angles of the pavilion and crown facets so that the greatest amount of light entering the stone is sent back to the crown. Otherwise, a washed-out area will appear in the middle of the stone and it is possible to see through the stone. In this case, the stone is said to have a "window" or a "fish-eye".

The inclination of the angles of the pavilion is much more important than those of the crown as the light should first reflect on the pavilion before reaching the crown. The chart in figure III gives the critical angle of the main pavilion facet in function of the refractive index.

---

[3] All angles in connection with gems, whether for incident, reflected or refracted rays, are measured from the normal: an imaginary line perpendicular to the surface.

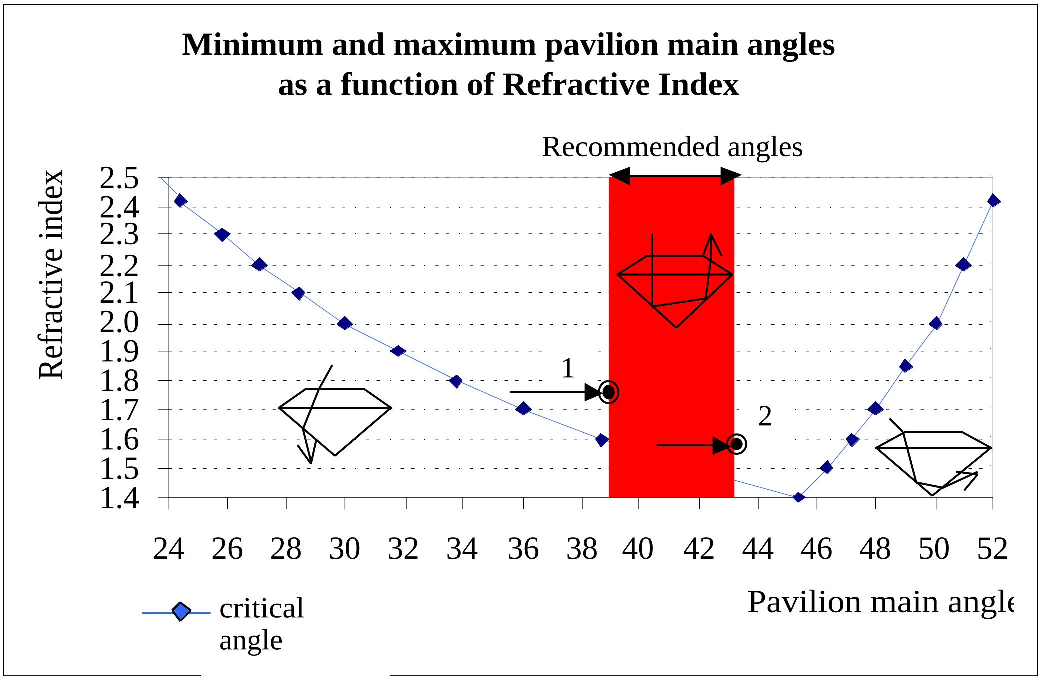

Fig. III

Recommended pavilion angles, from 39° to 43°, have been settled by the professional practice. The reason for cutting gems with pavilion angles no greater than 43° and no less than 39° is that it allows the gem to be tilted a number of degrees before most of the light is lost out of the pavilion.

Two examples with spinel and quartz :

1. RI of spinel is 1.72. Following the chart, it means that the critical angle is 35.8°. Two degrees should be added to allow a margin (38°), but the recommended angle is 39°.

2. The RI of quartz is 1.54. Following the chart, it means that the critical angle is 41°. Two degrees are added to get 43° which is within the upper limit of the recommended angle.

In general, good brilliance is obtained by cutting the crown angles from 40° to 50°, pavilion angles from 39° to 43° and the table about 50% of the diameter. Further discussions on optimal pavilion angle or crown angle or table size are intentionally avoided, as the subject is extensive and would go beyond the scope of this paper.[4]

[4] For more information, reference could be made to the research done by Long and Steele.

General consequences of the RI for the lapidary are summarised below:

- Pavilion angles should be adapted accordingly to the RI of the gem cut (refer to Figure III)
- For the light to reflect within the pavilion, no facets should be cut near the critical angle (two degrees above is a minimum). The closer the critical angle is approached, the less brilliance will result.
- Even if the crown angles are not respected, the brilliance of the stone will suffer far less than with wrong pavilion angles.
- A stone with a high R.I. will usually show a higher degree of brilliance, even if it is poorly cut.

2.4 Dispersion

Dispersion is the ability of a gemstone to split the light into its spectral colours. This colour dispersion produces beautiful plays of colour, also called fire. If the pavilion facets have returned the light rays to the crown, the crown facets may now disperse the light. Gems such as diamond, zircon or sphene have great potential to do this, while fluorite has almost none. In order to get dispersion, the crown facets must be correctly inclined to show it. Rays leaving a gem at normal[5] will show a minimum of dispersion (flat crown); those emerging at near critical angle show the maximum. Rays entering greatly away from normal will be dispersed when they enter, and further dispersed when they emerge.

Few stones are concerned with dispersion. Only benitoite, diamond, rutile, sphalerite, sphene and zircon have the strong ability to split the outgoing light into its spectral colours. The body colour of gemstone also tends to mask dispersion if the tone is medium to dark. Therefore this optical property is not essential for the lapidary, except for the few aforementioned stones.

2.5 Optic Axis

Minerals such as beryl, corundum, tourmaline are able to split the light into two separate rays which are polarised at right angles to each other. This effect is called birefringence, anisotropic or doubly refractive. With these gems the gem cutter is concerned with the optic axis. The optic axes[6] in a crystal are directions of single refraction in a birefringent material.

As a general rule, the table of a birefingent gemstone should be cut exactly at right angles to its optic axis. Under this condition the gem will pass the light from table to culet with little or no distortion. Otherwise the birefringence may be so strong that some gems may

[5] See footnote on page 4

[6] The optic axis of tourmaline or corundum is parallel to the vertical axis of the crystal – also called the c-axis in crystallography. The optic axis is referred to as the c-axis in the figures.

appear fuzzy. Fuzziness is ordinarily confined to minerals with a birefringence of .10 and higher noticeable in rutile, calcite, rhodochrosite, sphene and zircon. The fuzzy effect is minimised by the fact that it concerns relatively few gems and therefore is not of great concern for the faceter.

The isotropic or singly refractive minerals like fluorite, garnet, and spinel allow light to travel in all directions without any changes. As a result, these minerals without optic axes may be oriented in any way.

2.6 Pleochroism

Another optical property of gems of interest to the faceter is pleochroism and this property is closely related to the optic axes, discussed in the previous paragraph. Only minerals of the anisotropic group can split the light in two rays. These two rays may emerge in different colours or in two intensities of the same colour. The gems, which show the strongest pleochroism, are andalusite, axinite, corundum, iolite, spodumene, tourmaline and tanzanite.

Understanding the properties of pleochroism can help to produce fine gems of clear colour and conversely, ignoring it can devaluate a material by producing an unwanted colour. The best colour is seen along the c-axis while at right angles to this direction it is slightly less intense and of a slightly different hue.

With some stones, such as andalusite and zoisite, the pleochroism is an attractive quality and the stones are cut so as to bring out all the colours to best advantage. However, in ruby and sapphire, one colour is weaker and less attractive than the other is, so the orientation is best seen along the c-axis.

Unfortunately, weight retention or rough shape may lead to an inappropriate colour orientation. Stone 1 in Figure IV is correctly positioned, whereas stone 2 will show a blue colour of a lesser intensity. It is a good example of the trade-off a lapidary should consider in the colour orientation process.

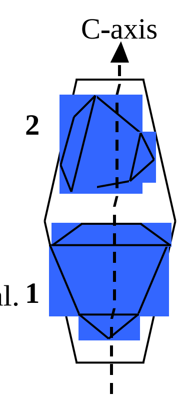

Fig. IV Gem orientation in a sapphire crystal.

2.7 Colour Zone

It is usual for coloured gem materials to contain bands and spots of colour. Amethyst, sapphire and tourmaline are well known gemstones with strong colour zones. Such colour variation within the rough must be oriented in order to get an even distribution of colour when the stone is viewed from the table. Therefore, the lapidary tries to orientate the stones so that the colour is placed at the culet. If it is not possible, the colour should be placed near the girdle area as shown in the figures below:

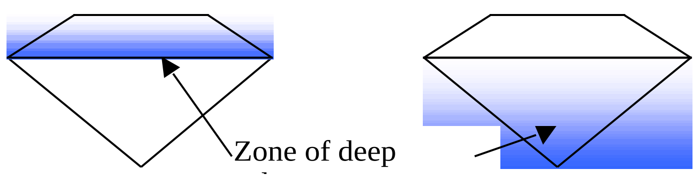

Fig. V - Orientation of colour zone

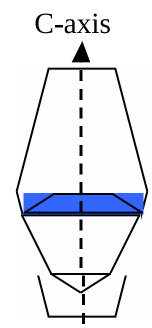

Fig.VI - Colour bands across a sapphire crystal

Some stones have an uneven colour distribution. For example, in ottu-type blue sapphires from Sri Lanka, colour lies just beneath the faces and at the tips of the crystal, with a colourless crystal core. For faceted stones to face-up the blue, the rough is oriented so that the colour lies at the culet, as already explained above, or across the crown

Stones 2 and 3 in Figure VII have the table lying parallel to the c-axis and as a consequence the colour will be less intense as pleochroism dilutes the colour. However, this orientation may be preferable to a partial lack of colour or a stone of a smaller size. Weight retention and colour orientation lead to an inappropriate cutting proportion. Stone 1 in Figure VII has a very deep pavilion which implies the possibility to have a window effect and further difficulties in the setting in a piece of jewellery. Example 3 in Figure VII has too shallow a pavilion resulting in an unavoidable fish-eye effect. Both stones give, once again, a good example of the decisions a lapidary should consider in the orientation process.

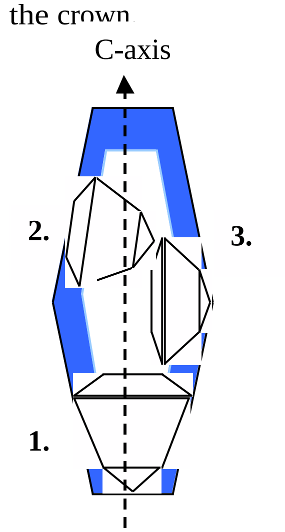

Fig. VII - Gem orientation in ottu-type blue sapphire

The colour zone of tourmaline shows different kind of distribution, either inside or along the crystal shape as shown in figure VIII & IX.

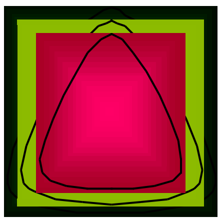

Fig. VIII - Coupe of a tourmaline crystal

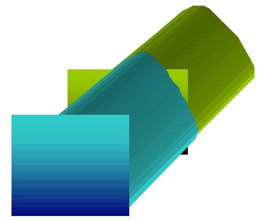

Fig. IX - Bi-coloured tourmaline crystal

With the crystal in Figure VIII, the lapidary is rather limited when using the faceting technique. Whenever the table is place along or perpendicular to the crystal, the light will pass through the different coloured layers. The resulting outgoing colour will not be attractive at all. Therefore, in this case, the best solution is to remove the thin green layers in order to get the most desirable pink colour in the centre despite the loss of weight.

The crystal in Figure IX is easier to handle with two practical solution. First, the green and blue sections can be sawed and faceted separately. Or second, the bi-colour effect is desired and only a step-cut will enhance the colour of both sections without distracting each other.

In conclusion, correct handling of the colour zone is crucial for the lapidary to get the best of the rough. Despite the fact that the occurrence is manifold, it is rather easy to see and very specific to mineral species. The challenge is getting the best colour with minimum weight loss.

2.8 Dark Coloured Material

When the rough must be viewed against a light in order to see the far side, the colour is considered to be dark. The goal in this case is to get as much light as possible through the gem in order to show the colour.

Whereas the colour is best seen parallel to the c axis, some dark Australian sapphires are intentionally oriented with the c axis at 45° or even parallel to the table to lessen the colour intensity.

This technique is also applied to dark green or blue tourmalines.

The colour across the crystal may be fine and clear, whereas the colour through the length of the crystal may be opaque. The effect is due, in part, to the polarisation of light through the c-axis and the deep body colour.

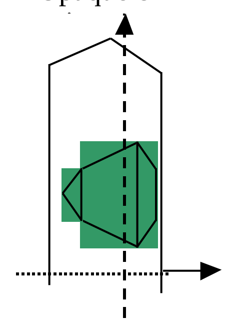

Fig. X Orientation of a green tourmaline

Very dark garnets are cut with the pavilion as shallow as possible in order to reduce the depth of the final gemstone. As garnets belong to the cubic crystal system, and pleochroism or the c-axis are not of concern, the rough orientation is only restrained by the shape of the rough.

It must be kept in mind that decreasing the hue automatically reduces the possibility of brilliance. The enhancing of colour by cutting a deeper stone also tends to reduce brilliance. The trade off is clearly stated, but, as colour is the more important characteristic of gems, the choice is easily made.

2.9 Cumulative Effects of Optical Properties

The optical properties of any gem, when considered together, have a profound effect upon the brilliance of the gem. The effect is dependent on the following characteristics in the following descending order: (1) clarity, (2) refractive index, (3) dispersion, (4) birefringence, (5) the density of colour. These five features are relative and may not carry the same weight in all gems, but their relative position in the descending scale cannot be ignored.

During the colour orientation of the rough, the lapidary must strive to balance desirable and undesirable features, all of which are interrelated to the initial shape of the rough, the weight yield and the stone's optical properties.

3 Appendix

3.1 Bibliography

Bariand Pierre & Jean-Paul Poirot (1998), *Larousse des pierres précieuses*, Larousse, ISBN 2-03-518200-X

Hughes Richard W. (1997), *Ruby & Sapphire*, RWH publishing ISBN 0-9645097-6-8

Pagel-Theisen Verena (1993), *Diamond Grading ABC*, 11th edition, Belgium, Rubin & Son bvba, ISBN 3-9800434-0-1

Perry Nance & Ron (1980), *Practical Gemcutting, A Guide to Shaping and Polishing Gemstones*, NY Arco Publishing, ISBN 0-668-05359-3

Read Peter G. (1999), *Gemmology*, 2nd edition, Oxford, Butterworth-Heinemann, ISBN 0-7506-4411-7

Schumann Walter (1997), *Gemstones of the World*, Revised & Expanded Edition, NY, Sterling Publishing Co., Inc ISBN 0-8069-9461-4

Sinkankas John (1962), *Gem Cutting, a Lapidary's Manual*, NY, Van Nostrand, ISBN 0-442-27623-0

Vargas Glenn & Martha (1989), *Faceting for Amateurs*, 3rd edition, CA,Thermal,

Watermeyer Basil (1991), *Diamond Cutting*, 4th edition, Perskor, Doornfontein, Johannesburg, ISBN 0-620-13248-5

Wykoff Gerald L. (1994), *The Techniques of Master Gem Polishing*, NY, Adamas Publishers, ISBN 0-9607892-9-4