Accordance in round brilliant diamond cutting

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Abstract: *Over more than 150 years, those involved in the diamond industry have worked to establish the ideal angles and proportions to cut the facets of the Standard Round Brilliant (SRB) diamond in order to produce the 'Ideal' gem. This paper reviews milestones in that work and demonstrates that the solutions by major contributors to this endeavour have surprising commonalities. These common aspects are in accord with the research and investigation of the author as well as the knowledge of diamond cutters and the teaching of diamond cutting institutions.*

Keywords: *cut grading, diamond, round brilliant*

Introduction

The 57-facet Standard Round Brilliant cut (SRB) has evolved over several hundred years. Its finest cut quality has historically been called 'Ideal'. Many consider the Ideal Round Brilliant style of cut superior because its cut quality (called its 'make') brings out the best in diamond beauty, brilliance, fire and sparkle. The quality of these attributes of diamond beauty is referred to as the diamond's 'optical performance' or its 'light performance' (Cowing, 2005).

Diamonds in a range of cut proportions that are seen by diamond cutters and many other experienced observers as having greatest beauty possess the best combination of brilliance, in both its aspects of brightness and contrast, fire, and scintillation (sparkle with movement) (Cowing, 2005). This is the essence of the 'Ideal Round Brilliant'.

Today, consumers in increasing numbers are looking for diamonds with the best possible beauty, i.e. the best light performance. They look to jewellery retailers for proof of perfection of cut. In turn, the jewellers often look to the diamond grading laboratories or gemmologist-appraisers for assistance in providing consumers with confirmation of the quality of their diamond's make.

The laboratories of the Gemological Institute of America (GIA) and the American Gem Society (AGS) appear to be divided as to the finest or ideal make in the round brilliant diamond. The AGS believes "Tolkowsky was right" (Bates, 2004) and that the angles and proportions within a narrow range of the Tolkowsky Ideal have the best optical performance. The GIA has found: "There is no one set of proportions that yields the most beautiful diamond" (Boyajian, 2004). Instead, there are many different proportion sets that are seen as top performers. "The long-held view that expanding deviations from a fixed arbitrary set of proportion values produces diamonds with increasingly poorer appearances is simply not valid" (Boyajian, 2004).

GIA's grade or measure of make has five levels. The highest is 'Excellent'. The range of angles and proportions that attain the GIA 'Excellent' grade is larger than that of the AGS 'Ideal 0' grade. Although there are significant differences, the 'Excellent' grade is best compared to the top two grades of the 11 grade AGS system, each comprising the top approximately 20% of the grades in both systems.

Several diamond cutting houses and retailers, some grading laboratories, and some gemmologists and researchers including the author, set the bar for the best make higher in some respects than either GIA or AGS. In a sense you could say that they answer to a higher authority. For this investigator, that authority comes from a "direct assessment" of the diamond's optical performance in typical illumination circumstances (Cowing, 2005).

Consider the commonalities

The question is how to reconcile the differing viewpoints. The answer is found by considering aspects that these different viewpoints have in common. I find that there are more aspects of agreement among the cut grading systems than disagreement. To discover the best round brilliant diamond make, let's look at the aspects in common between the grading systems of all these groups rather than their differences.

The round brilliant cut sweet spot

If you play or watch golf or tennis, no doubt you will have heard about the 'sweet spot'. This is the area near the middle of a club or racket where the ball is struck with maximum control and speed. Striking the ball within the sweet spot causes it to respond with the best, most consistent performance.

There is also a 'sweet spot' in terms of cutting angles and proportions for peak diamond performance. The range of this sweet spot encompasses pavilion and crown angles long associated with the 'Ideal' cut. In this sense, the range of angles and proportions said by GIA and AGS to give the best brilliance, fire and sparkle, are their respective sweet spots. When the cutter fashions the diamond with sufficient craftsmanship to obtain a diamond within the sweet spot range, the diamond responds with the best light performance and beauty.

In tennis the best athletes use a racket with the largest sweet spot and aim to hit its centre. In diamond design, the evolution of the 'Ideal' round brilliant has led cutters very close to the centres of the sweet spot of both grading systems. Today's cutters aim close to the centre of the round brilliant's sweet spot when they want to ensure the best light performance and beauty.

Seven parameters are used today to define the round brilliant cut. (Standard 'indexing' or placement of each facet is assumed). These seven parameters are the pavilion main angle, the crown main angle, the table size, the length of the pavilion halves (lower girdle facets), the length of the star facets, the girdle thickness and the culet size. What is most remarkable is the finding of close agreement in the locations of the centres of each group's sweet spot in all seven of these parameter dimensions. As an aid in discussing these parameters, here are descriptions and illustrations of the anatomy of a round brilliant.

Anatomy of the 57-facet round brilliant cut

The round brilliant cut has two key parts, the top and the bottom known as the crown and pavilion. The diamond's crown and pavilion are joined together at the girdle, where the diamond is at its maximum width.

The Crown

Most of the brilliance, fire and sparkle reflected to our eyes from within the finest round brilliant cut diamonds comes from light that entered the diamond through its

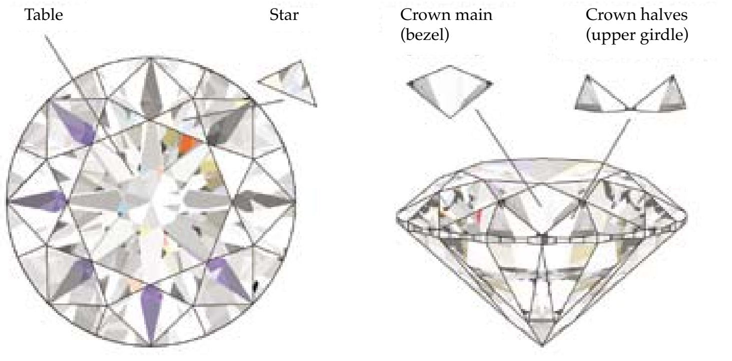

Figure 1: Names of the crown facets shown in face-up and perspective views.

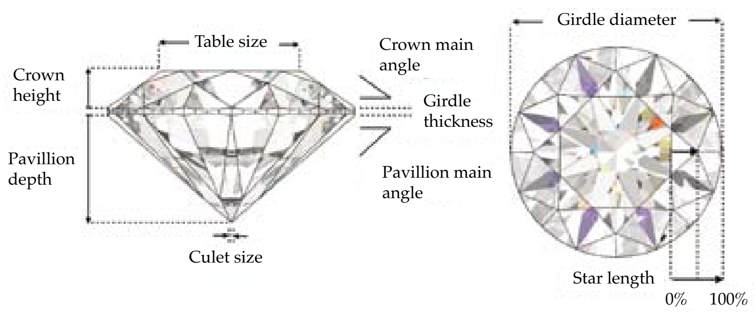

Figure 2: Angles and proportions of the standard round brilliant cut. Note that table size is measured from corner to corner as labelled in the side view where the crown main facets are on edge.

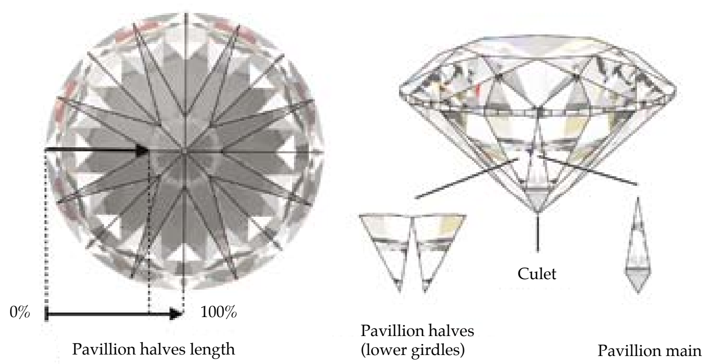

Figure 3: Pavilion facets from bottom and perspective views.

top section, the crown (see *Figure 1*).

The largest facet, which is centred on the crown, is the octagon-shaped table. Eight triangle-shaped facets called stars surround it. Next are the eight kite-shaped facets called crown mains or bezels. The sixteen crown halves follow the mains. These are also called upper girdle facets, because one of their three sides forms the upper outline of the girdle.

The parameters that uniquely define the crown of the standard round brilliant are shown in *Figure 2*. They are the crown main angle, the table size, the angle of the crown halves and the star angle. An alternative to listing the angle of the crown halves and the angle of the stars is to specify the star length percentage. The star length determines the angles of the stars and halves in the context of a specific crown main angle and table size.

The pavilion

Below the girdle is the pavilion, which is the principal light-reflecting portion of the round brilliant (*Figure 3*).

The pavilion is comprised of 16 pie-shaped pavilion halves, also called lower girdle facets. Eight pavilion main facets intersect the pavilion halves. A small, octagon shaped, 58th facet may be present at the tip of the pavilion. This point, where the eight pavilion mains come together, is the culet, and this 58th facet is called the culet facet.

All the brilliance, fire and sparkle our eyes see emerging from within the round brilliant through its crown is reflected from either the pavilion mains or the lower halves. Changes in the sizes and angles of the pavilion mains and halves have the greatest effect on the diamond's beauty and optical performance.

The girdle

The girdle is the thin section whose surface forms the diamond's perimeter. It joins the crown and pavilion. The upper and lower girdle facets, commonly called the halves, form the girdle's scalloped boundaries. The girdle itself may be polished or unpolished. Today it is generally faceted, as shown in *Figures 1, 2* and *3*.

Facet alignment

In the round brilliant cut, the crown and pavilion halves are aligned across the girdle. The tail of the crown main, kite-shaped facet lines up directly across the girdle from the sharp point of the pavilion main facet.

Tolkowsky's theory and Morse's Ideal angles

In the 1860s, Henry D. Morse, founder of the first successful American diamond cutting firm, discovered the centre of the diamond's sweet spot in two of the most important of the seven parameters. These are the pavilion main angle and the crown main angle. This was the greatest single stride in the evolution of what today is known as the 'Ideal'. A half-century later, the engineer and diamond cutter, Marcel Tolkowsky (1919) validated these angles theoretically using arguments based on both mathematics and physics.

Since that time, the term 'Ideal Cut' has come to be associated with the angles and proportions of Tolkowsky's theoretical determination. These are a pavilion main angle of 40.75°, a crown main angle of 34.5° and a 53% table. However, this definition of the 'Ideal' is incomplete because it addresses only 17 of the 57 important facets defining the round brilliant cut diamond, and the range of the theoretical sweet spot for pavilion angle, crown angle, and table size is not addressed.

Because of the historical overemphasis on Tolkowsky's theoretical angles of 40.75° and 34.5° in association with 'Ideal', it is important to know that the five diamonds that Tolkowsky listed in his book as examples of maximally brilliant diamonds, had pavilion angles from 40° to 41°, and crown angles from 33° to 35°. These figures provide an implicit sweet spot range. Additionally, Tolkowsky notes in his book that American writers credit Henry D. Morse with first cutting for "maximum brilliancy". The angles that Morse first discovered that were said by writers like Frank B. Wade (1916) and Herbert Whitlock (1917) to yield an 'ideal brilliant' had a range that centred on a 41° pavilion and a 35° crown.

The centre of the range of Ideal

Frank Wade was an American diamond expert who greatly influenced the thinking about the 'Ideal' cut. He said of Morse's angles: "Within the limits of one or two degrees there is little variation in brilliancy." This accords with today's consensus that there is a range of appropriate angles and proportions producing the best optical performance and beauty. This article calls that range the diamond cutting sweet spot. Differences of opinion are principally in the extent of variation in angles and proportions from those of Morse and Tolkowsky that retain the finest brilliance, fire and sparkle.

It is worth looking at those variations and the centre of the round brilliant cut diamond's sweet spot for not only the crown and pavilion main angles, but all seven of the parameters that define the important facets making up the round brilliant cut.

Comparing the centres of the sweet spots

We compare the GIA's 'Excellent' range of crown and pavilion main angles in their 5 grade system and the top two grades in the AGS's 11 grade system, because both comprise approximately the top 20% of each laboratory's grading system. Because of the interaction and interrelationship between the diamond's parameters, they must be considered in relation to each other. This is why both GIA and AGS provide charts for each table size showing the range of crown and pavilion main angle combinations that comprise each grade.

Centre of the sweet spot for the table

Figure 4 shows, for each table size, the number of combinations of crown and pavilion main angles that may attain the top grade in GIA's and AGS's grading systems.

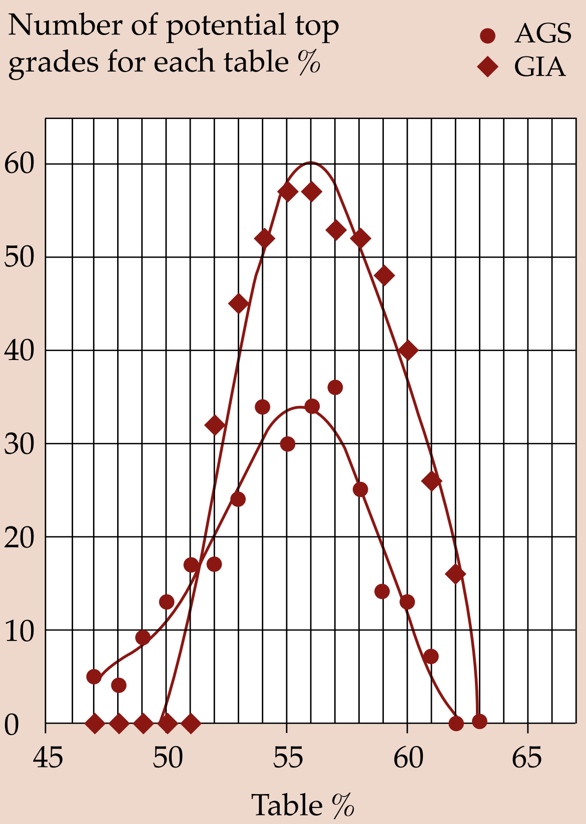

Figure 4: Number of combinations of crown and pavilion main angles for each table percentage that may attain the top cut grade.

A visual assessment of the peak area of each of these curves indicates that the centre of the sweet spot of the table size is closest to 56% in both grading systems. These two curves indicate that table sizes within 2% to 3% of the sweet spot centre of 56% contain a majority of the best combinations of crown and pavilion main angles.

Sweet-spot centre for the crown and pavilion angles

Let us analyze the combinations of crown and pavilion main angles that receive the top grades in each system for a 56% table. The centres of the GIA and AGS sweet spots are compared with the Morse and Tolkowsky 'Ideal' angle combinations in *Figures 5, 6* and *7*.

The sweet spot of potential 'Excellent' combinations of crown and pavilion angles is outlined in red in *Figure 5*. It has as its centre, indicated by the red spot, a pavilion main angle of 41.2° and a crown main angle of 34.0°. Shown in cyan and green are the Tolkowsky angle combination of 40.75° and 34.5° and the Morse angle combination of 41° and 35°.

GIA 'axis of Excellent'

Also shown in *Figure 5* is the negative slope of approximately -4.5 to 1 (red line) that is the axis of the sweet-spot for crown and pavilion angle, the 'axis of Excellent' (The major axis of an ellipse fit to the 'Excellent' sweet spot would have this approximate slope.) Although the GIA 'axis of Excellent' is shown as a line, it is not necessary to be on that line in order to attain the 'Excellent' grade. The slope of this line indicates that a change in pavilion angle from either Morse's or Tolkowsky's angles is best compensated by a 4.5 times change in crown angle in the opposite direction. Notice that Morse's angles are closest to that line. Tolkowsky's angles are in the 'Excellent' range and only slightly shallower by 0.25° in pavilion angle and 0.5° in crown angle.

Figure 6 is the corresponding AGS cut grade estimation chart for a 56% table. The sweet spot of potential AGS 0 and 1

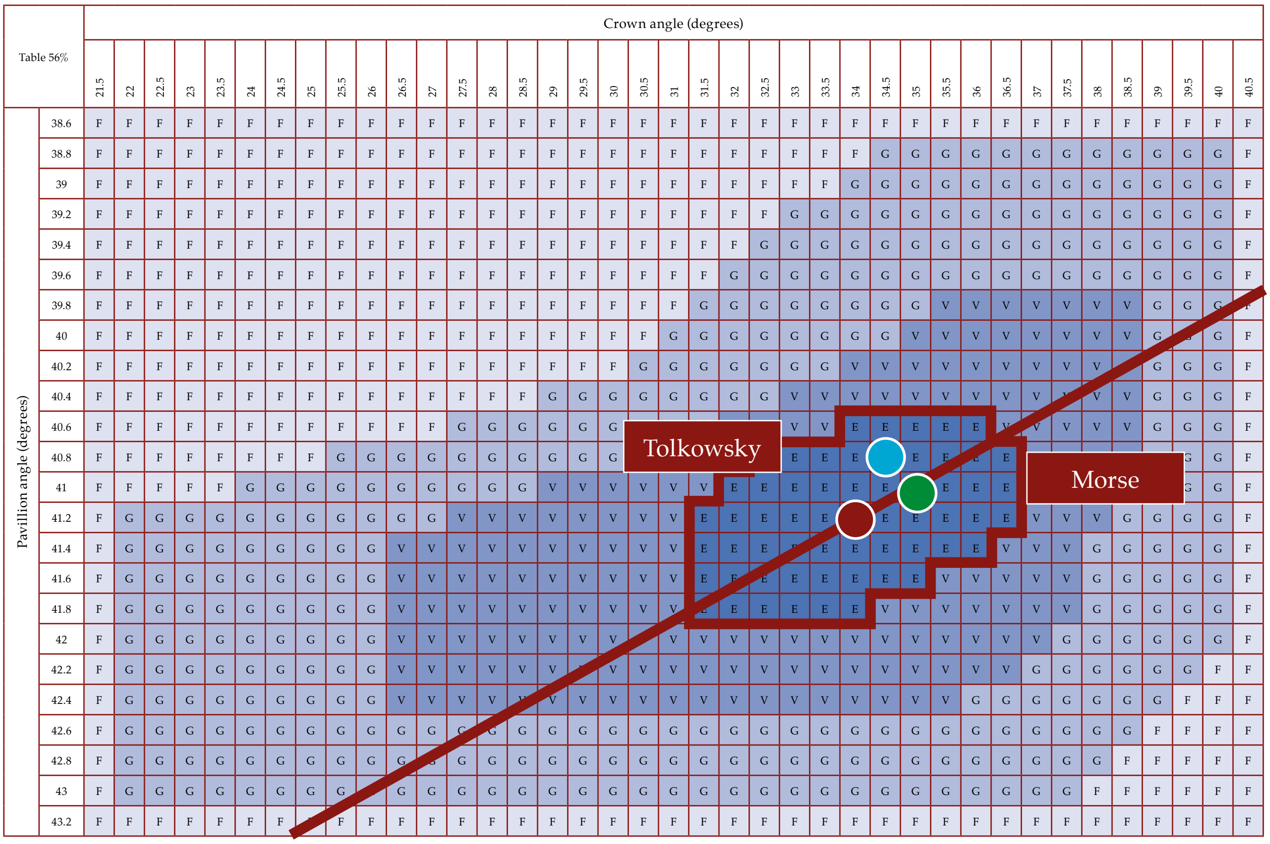

Figure 5: GIA cut grade estimation for a 56% table. The 'sweet-spot' of potential 'Excellent' combinations of crown and pavilion angles is outlined in red. It has as its centre a pavilion main angle of 41.2° and a crown main angle of 34.0° (red spot) compared to the Tolkowsky angles of 40.75° and 34.5° (cyan spot) and the Morse angles of 41° and 35° (green spot).

combinations of crown and pavilion angles is outlined in blue. It has as its centre, shown with the blue dot, a pavilion main angle of 41.1° and a crown main angle of 33.75°

Remarkably, this centre of the sweet-spot for the top 20% of the AGS cut grades has the same pavilion angle within a tenth of a degree and a crown angle that is within a quarter degree of the corresponding centre of GIA's 'Excellent' grade.

AGS 'axis of Ideal'

The axis of best angle combinations for the AGS 0 and 1, the 'axis of Ideal', also has about the same -4.5 to 1 negative slope as the GIA's 'axis of Excellent'. Tolkowsky's angles fall nearest this axis of best angle combinations. Morse's angles of 41° and 35° are just slightly steeper in crown angle and slightly deeper in pavilion angle. Notice that this range of AGS Ideal 0 and 1 grades, although having a similar slope as the GIA 'axis of Excellent', is much narrower. It excludes Morse's Ideal angle combinations from the top two grades. Clarification on this point was obtained from AGS (P. Yantzer, pers. comm.) He indicated that the AGS charts are guidelines for the cutters, and the range of AGS 'Ideal 0' is somewhat wider than is shown by their charts. For example, Morse's 'Ideal' angles of 41° and 35° in proper combination with the other five parameters do attain the AGS 'Ideal 0' grade. This is in spite of the chart's indication that the combination of 41° and 35° is an AGS 2.

Figure 7 is a combined comparison of the AGS 'Ideal 0 and 1' sweet spot with that of the GIA 'Excellent' showing their overlap and the close agreement of the sweet spot centres. So based upon the charts of both GIA and AGS, we observe that the target centre of the sweet-spot of the best round brilliant cut is Morse's 41° for pavilion angle and closer to Tolkowsky's crown angle of

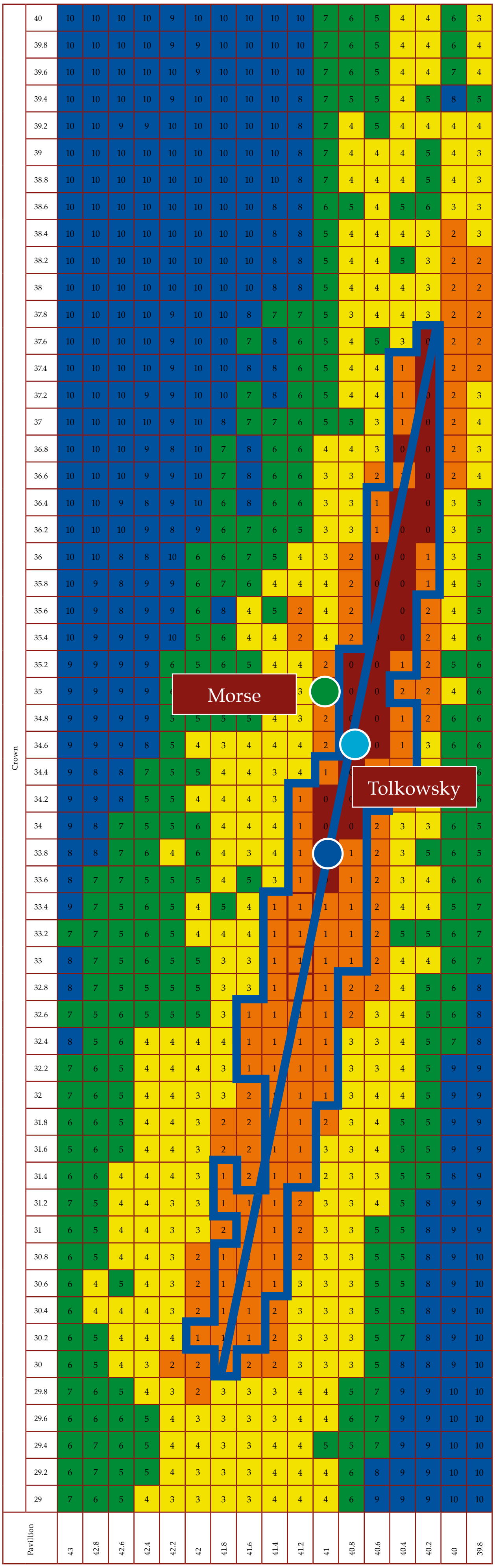

Figure 6: AGS cut grade estimation for a 56% table. The 'sweet-spot' of potential AGS 0 and 1 combinations of crown and pavilion angles is outlined in blue. It has as its centre a pavilion main angle of 41.1° and a crown main angle of 33.75° compared to the Tolkowsky angles of 40.75° and 34.5° and the Morse angles of 41° and 35°.

34.5° at 34°. Both 41° and 34° are very close to both the angles of Morse and Tolkowsky. In proper combination with the other five parameters, this sweet-spot centre of 41° and 34° along with the angle combinations of Morse and Tolkowsky all have ideal optical performance and beauty.

This sweet spot centre accords well with this investigator's findings based upon his direct assessment of the diamond's optical performance in typical illumination circumstances. The sweet spot centre of 41° and 34° is also in accordance with the teaching of diamond cutters and diamond cutting institutions. For example, from the 1970s the Institute for Technical Training in Antwerp, Belgium, taught angle combinations of 41° and 34° - 34.2° (pers. comm., D. Verbiest). In the same time frame, but a continent away in Johannesburg, South Africa, the Katz Diamond Cutting Factory was teaching its apprentices to cut the 'Ideal' round brilliant to a 41° pavilion main angle and 33° to 35° crown main angle (pers. comm., P. Van Emmenis).

What about the centre of the sweet spot for each of the other 4 of the 7 parameters defining the round brilliant?

The importance of the length of the pavilion halves

There is general agreement that it is the interrelationship of all the individual proportions that determine the diamond's performance and beauty. However, the diamond's light performance is most sensitive to changes in the pavilion main angle, the crown main angle and the length of the pavilion halves (lower girdle facets.) We can explore the range of the pavilion

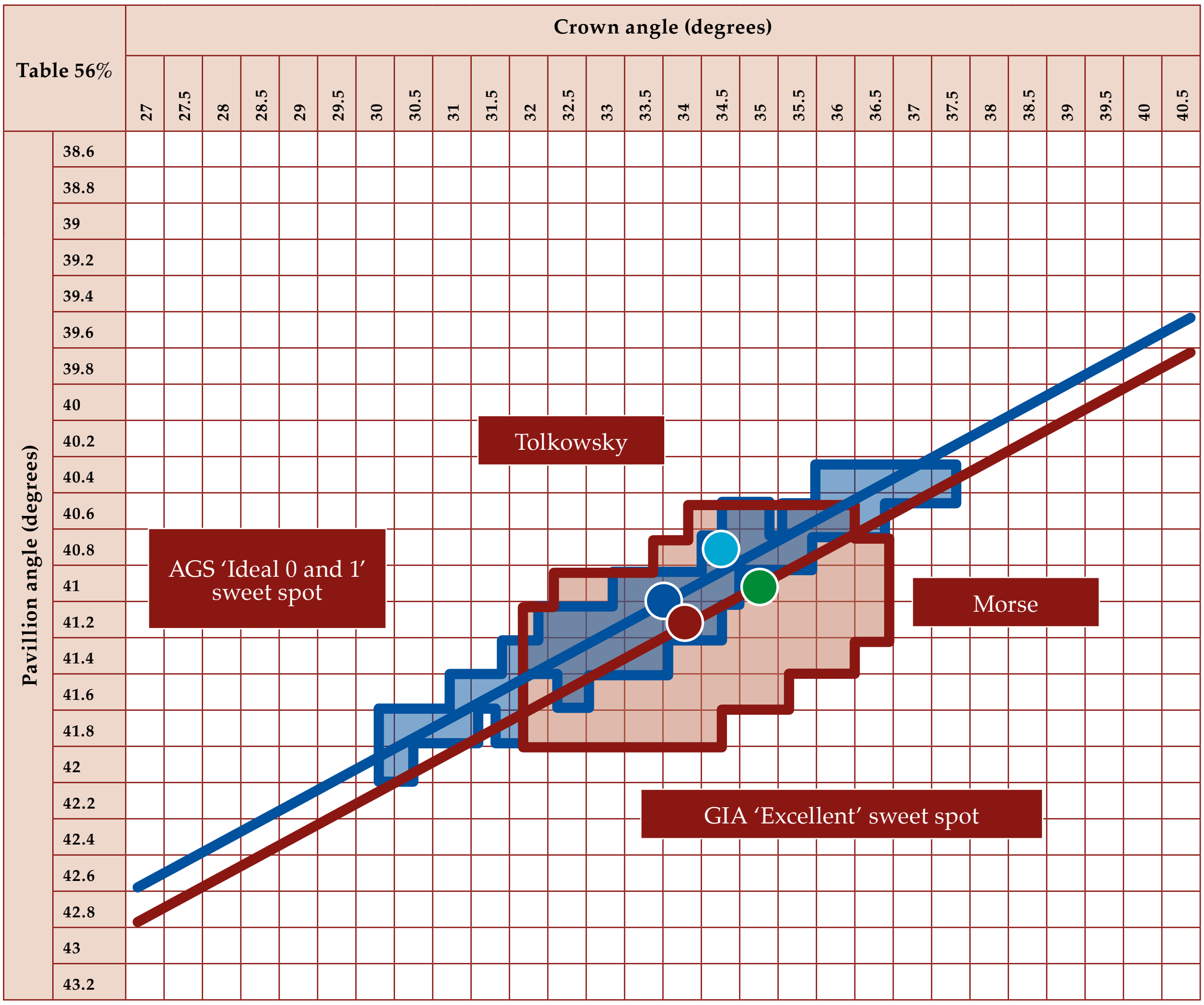

Figure 7: A comparison of the AGS 'Ideal 1 and 0' (blue) sweet spot with that of the GIA 'Excellent' red showing their overlap and the close agreement of the sweet spot centres.

halves and the other parameters in the context of the sweet spot centres of the table size, crown angle and pavilion angle.

In the early nineteenth century and before, most of the area of the pavilion was occupied by the main facets, which dominated the diamond's reflection pattern. As can be observed today in 58 facet, triple-cut diamonds from that era, the halves were small compared to those of the modern round brilliant. (Triple cut is the term from the nineteenth century for the early 58 facet brilliant cut (Tillander, 1995) that today is popularly referred to as an Old European Cut (Gaal, 1977).) At that time the pavilion halves extended less than half the way to the culet. In contrast, Tolkowsky indicated in his book in 1919 that the high-class brilliant had lower halves two degrees steeper than the pavilion mains. This resulted in a length of the lower halves of about 60%, which was a significant increase in the length and size of the halves

Figure 8: Modern 'Ideal' round brilliant cut (1.00 ct) and early triple-cut (2.38 ct) under the same 'fire friendly' illumination.

from those earlier times.

During the twentieth century, the pavilion halves were further increased in length with consequent increase in their area and influence on the diamond's beauty. The motivation for this increase in the length of the halves was the increased amount of sparkle or scintillation brought about by larger halves. However, a consequence of the increase in the halves in order to favour scintillation was a decrease in the size of the main facets. This brought an accompanying reduction in the desirable properties of large flash sparkle and fire that result from larger mains. This large flash fire and sparkle was a fundamental aspect of the appeal of the early round brilliant from the times of Morse and Tolkowsky.

Figure 8 shows a 2.38 ct early triple-cut diamond with shorter pavilion halves compared to a 1 ct, 'Ideal' round brilliant with approximately 77% lower halves. Both were photographed in the same 'fire friendly', high contrast, spot illumination. This is lighting favourable to the display of fire. Both are impressive demonstrations of the diamond's fire resulting from white light dispersed into colours of the spectrum. However, larger flashes of fire, due principally to larger mains, are apparent in the early triple-cut compared to the more numerous but smaller flashes of fire in the 'Ideal' cut.

In illumination that is more favourable to brilliance and sparkle, such as that in a typical jewellery store, the comparison between diamonds with shorter and longer pavilion halves reveals a similar contrast in their light performance. That contrast is between the large flashes of brilliance, fire and sparkle due to the larger mains of the early 'Ideal' cut and a greater amount of smaller sparkle and fire due to the larger halves and thinner mains of the modern 'Ideal' cut. To further demonstrate this contrast, a modern 'Ideal' cut was simulated (*Figure 10*) with proportions similar to those of the 'Ideal' cut photographed and shown in *Figure 9*. (Comparison of the actual photograph to the computer simulation of the diamond demonstrates the photo-realism and utility of today's computer imaging technology.)

Changing just the length of the lower halves of the diamond in *Figure 10* to the 60% of Tolkowsky's time, causes the diamond's mosaic pattern of reflections to return to the large flash brilliance and fire in *Figure 11* that characterized the beauty and appeal of the older brilliant cuts. At the same

Figure 10: *Computer image of a similar 'Ideal' cut diamond in typical viewing and illumination circumstances. The simulated diamond is inset at a smaller magnification to enable comparison at closer to actual size.*

Figure 9: *Photograph of an 'Ideal' cut diamond in typical viewing and illumination circumstances.*

Figure 11: *Computer image of the identical 'Ideal' cut diamond except for a 60% length of the lower halves. The simulated diamond is inset at a smaller magnification to enable comparison at closer to actual size.*

time, we can appreciate in the modern 'Ideal' the retention of large flashes along with more numerous smaller flashes of sparkle and fire evident in *Figures 9* and *10*.

This comparison of optical performance and the previous one in *Figure 8* support the observation that an attractive balance between the areas occupied by the mains and halves is necessary for these two central reasons.

A number of individuals, diamond manufacturers, and this investigator agree that the best balance between the area of the main reflections and the area of the halves is obtained with a 75% to 80% length of the pavilion halves. This is the sweet spot range of lower half length that retains the large flash sparkle and fire and at the same time provides a greater amount of scintillation. The range of possible GIA 'Excellent' lower girdle facet lengths is 70% to 85%. Both ranges have the same 77.5% as the centre of the sweet spot of lower half length.

Agreement on the parameters of girdle and culet size

Of the seven parameters, those of girdle thickness and culet size have the least influence on the brilliant cut's light performance. There is general agreement regarding these two parameters. The noticeably large culets of the past have been determined to detract from diamond beauty. Because it is parallel to the table, a large culet facet appears like a lifeless, dark 'window' in the diamond's centre. This can be seen in the early triple-cut in *Figure 8*. The culet facet has been minimized or eliminated in the modern round brilliant. The girdle thickness is kept thin to medium for two reasons. Any less thickness increases the vulnerability to chipping, and any greater thickness causes the diamond's apparent size (which the trade calls 'spread') to appear noticeably smaller than would be expected for its weight.

Sweet spot centre of the star length

That leaves just the star length as the remaining parameter to consider. In the context of the table size and crown main angle, the star length determines the angles of the star facets and the crown halves or upper girdle facets. Although having less impact on diamond beauty than the pavilion mains and pavilion halves, the angles of the crown halves and stars do influence the diamond's light performance. Star lengths of 45% to 65% have the potential to receive a GIA 'Excellent' cut grade. This makes 55% the centre of the GIA sweet spot for star length. This accords with the findings of this investigator and the practice of many of today's cutters of the modern 'Ideal' cut. We find that the best optical performance is obtained with a star facet length between 50% and 60%, centred at the same 55%.

Summary of the seven-parameter sweet spot centre

For a round brilliant cut diamond, the finest or ideal beauty is attained in the narrow range of parameters that in this paper is called the sweet spot. This is the range of angles and proportions historically called 'Ideal', where the round brilliant cut exhibits the best distribution of brilliance (in both its aspects of brightness and contrast), fire and sparkle in typical real world illumination circumstances. Essential to this concept of 'Ideal' is the balance of the properties of reflections from the pavilion main facets and the pavilion halves (the lower girdle facets.)

Considering the GIA and AGS sweet-spot parameter centres and the knowledge gained from his own research, the author concludes that the seven-dimension, sweet-spot centre for the 'Ideal' round brilliant is as follows:

Listed in order of parameter importance:

1. Pavilion main angle = 41°
2. Length of pavilion halves = 77%
3. Crown main angle = 34°
4. Table size = 56%
5. Star Length = 55%
6. Girdle size = thin to medium
7. Culet size = small to none

These proportions accord with the author's knowledge of the parameters that yield the essence of ideal beauty in the standard round brilliant. That understanding is based upon direct assessment of the diamond's optical performance in typical real world illumination circumstances. There remain many important differences among the various grading systems, but we can all agree upon the centre of the 'Ideal' cut diamond's sweet-spot.

A conclusion reported by Cowing (2000) was that diamond cutters were correct in their adherence to close to a 41˚ pavilion angle. This angle is the most critical of the diamond's parameters. Further research by the author into all seven of the parameters that define the round brilliant has validated the accomplishments and progress of diamond cutters from the times of Morse and Tolkowsky until today. They would likely approve of today's 'Ideal' round brilliant, which evolved from their key contributions to the art and science of diamond fashioning.

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The causes of colour variation in Kashan synthetic rubies and pink sapphires

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Abstract: *The trace element patterns of Kashan synthetic rubies and pink sapphires reveal two colour-causing transition metal elements, chromium and titanium, which are present in ranges of concentrations up to 0.23 wt.% TiO_2 and up to 0.62 wt.% Cr_2O_3. UV-visible absorption spectra consist of the absorption bands of Cr^{3+} on which the absorption bands of Ti^{3+} are superimposed. The titanium component of the spectra predominantly removes the purplish tint of the ordinary ruby colour and thus the saturated red or even orangey red coloration of the synthetic Kashan corundum material is developed. By heat treatment in air, titanium is oxidized from Ti^{3+} to Ti^{4+} and the influence of titanium on the ruby colour is removed.*

Keywords: *Heat treatment, Kashan, synthetic ruby, trace elements, visible-range spectra.*

Introduction

Reference samples of natural and synthetic gem materials are frequently used in gemmological laboratories. In general, the properties of natural reference samples of known origin or the features of synthetic reference samples of a known producer are compared with properties of samples of unknown origin which are submitted for examination. In other cases, analytical instruments are calibrated using reference samples with known properties, e.g. of known chemical composition. During a re-examination of the properties of a large suite of Kashan synthetic rubies, the authors have observed some chemical and spectroscopic properties related to the causes of colour within these samples which have only briefly been mentioned in the gemmological literature. In particular, the causes of colour and the correlation of trace element contents with spectroscopic properties in Kashan synthetic rubies have not been described and understood in detail.

Kashan synthetic rubies were produced by Ardon Associates in Austin, Texas, U.S.A., from the end of the 1960s to the mid-1980s with a short renaissance in the mid-1990s (Nassau, 1990; Laughter, 1994; Kammerling *et al.*, 1995; Hughes, 1997). The synthetic rubies are flux-grown from a cryolite-bearing melt (Gübelin, 1983; Henn and Schrader, 1985; Schmetzer 1986 a,b). Compared to various natural and synthetic rubies, some of the Kashan crystals contain unusually high titanium in the range of 0.04 to 0.17 wt.% TiO_2 (Kuhlmann, 1983; Muhlmeister *et al*., 1998) with high titanium contents reported especially for pink samples (Gübelin, 1983). These relatively high amounts of titanium are, most probably, related to an unusual pleochroism observed in part of the Kashan material with an extraordinarily strong yellowish red or orange parallel to the *c*-axis (Gübelin, 1983; Hughes, 1997). From the examination of absorption spectra it is known that some Kashan synthetic rubies reveal an absorption band due to Ti^{3+} in addition to the ordinary Cr^{3+} absorption spectrum (Schmetzer, 1986 b, p.102). This titanium-related absorption band reduces the violet to purplish tint of chromium on its own in many 'ordinary' rubies or pink sapphires (see Box).

Materials and methods

For the present study, the authors examined 70 Kashan synthetic rubies in the range of 0.14 to 3.05 ct in weight, originating from the reference and teaching collection of one of the authors (DS) and from other reference collections. The samples (*Figure 1*) show clear ranges in colour from purplish pink to pink and orangey pink, and from purplish red to red and orangey red. In general, those samples with a less intense violet or purplish tone tended to resemble 'Thai rubies', and those with a somewhat more intense violet to purplish hue tended to resemble 'Burmese rubies'. All 70 stones showed a small shift of colour between daylight and incandescent light.

Figure 1: *Six Kashan synthetic rubies and pink sapphires showing a wide range of colour representative of our research material. Weight of samples from 0.96 to 1.60 ct, the sample at the lower left weighs 1.05 ct and measures 5 × 7 mm. Photo by H.A. Hänni.*

Trace or minor element contents of all 70 samples were obtained using EDXRF spectroscopy. The analyses were performed with a Tracor Northern Spectrace 5000 system, using a programme specially developed for trace element geochemistry of corundum. The detection limit for these minor elements was in the range of 0.005 wt.%; consequently below detection limit (bdl) indicates a concentration below 0.005 wt.%.

Polarized UV-Vis absorption spectra of 15 samples with different trace element contents, especially with different titanium concentrations, were recorded with a Perkin-Elmer Lambda 19 spectrophotometer after orientation of the optic axis of each sample with the aid of an immersion microscope. Heat treatment of four samples with high titanium contents was performed in air at 1750°C over a period of 170 h, and then their polarized absorption spectra were recorded again.

Results

Chemical properties

On visual inspection, the synthetic rubies show a continuous range of colour (*Figure 1*) and cannot be subdivided into groups with specific colours. This visual impression is confirmed by their chemical compositions. EDXRF spectroscopy shows that two major colour-causing trace elements, namely chromium and titanium, are present with chromium contents between 0.09 and 0.62 wt.% Cr_2O_3 and titanium contents from bdl

According to a general practice in the gem trade, we are using the terms 'ruby' and 'pink sapphire' for chromium-bearing synthetic corundum. However, we would like to mention that there is no clear boundary between the two varieties due to a continuous range of chromium contents within the Kashan material.