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A ray tracing study of gem quality

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Abstract. A computerized three-dimensional ray tracing technique is utilized to obtain the scattered pattern of light perpendicularly incident on the table of gem stones. It is then shown that a correlation exists between gem cuts considered best by the diamond trade and the reflection pattern within a cone angle of about 60°.

1. Introduction

The optical properties of gemstones in general and diamonds in particular are closely related to their 'beauty'. The beauty of a gem is revealed through the light being reflected by the stone and depends primarily on the material's index of refraction and the shape in which it is cut. It was not until the early 20th century, however, that an attempt was made to define mathematically the properties of beauty [1]. Till then the cutting was solely an art which was expressed by the broad spectrum of diamond designs, most of them no longer in use. Nowadays, the most popular is the so-called brilliant cut [1], which is a 58-facet, eightfold symmetric design. Using a simplified two-dimensional model, together with geometric and optical arguments, Tolkowsky [2] was able to justify the shape and number of facets of that cut. Furthermore, he defined a criterion for beauty which served to find the most desirable proportions of the stone's facets. Tolkowsky's proportions are still accepted by the Gemmological Association of America as the best ones proposed so far. Alternative, though similar, approaches by Johnson [3] and Eulitz [4] produced other sets of proportions. A technique developed by Rösch [5] and later used also by Elbe [6], to approach the problem experimentally, produced a spot diagram of the light scattered by a gemstone. Recently a laser technique has been utilized [7] to obtain reproducible pictures of the scattered light, in order to be able to identify uniquely individual cut diamonds, for purposes such as insurance, etc. This technique made visible many spots otherwise not perceivable and one could notice that some relation exists between the scattered spots and the quality of the diamond cut. Thus, we attempted a computer study of gem cuts [8], by simulating and ray tracing the scattered light. That program was motivated by a goal to define realistic and useful criteria for diamond beauty in order to take the 'art' out of the trade and set it on better, more easily controlled and measurable parameters. More recently, Dodson [9] took advantage of the computer ray tracing approach in order to evaluate three statistical parameters which he associated with the previously more intuitive definitions of beauty, namely brilliance, sparkliness and fire. As a consequence of his study, Dodson proposed some new cut designs which he considers to be comparable to the traditional one, or even more attractive.

It is the purpose of the present paper to outline the computer ray tracing method of [8] and bring together some characteristic results in an attempt to correlate some commonly used cuts with the subjective cut quality criteria as determined by experts in the diamond trade. A general description of the computer model is given in § 2. Its application to some selected cuts is discussed in § 3. Suggestions for further investigation in the light of our conclusions are presented in § 4.

2. The computer model

The experimental set-up [7] simulated by our computer program is schematically described in figure 1. The lens L has a twofold purpose: first, to transpose the source light S into a collimated beam of parallel rays which impinge on the diamond D, and secondly, to collect the reflected light on a screen SC in order to obtain the far-field pattern within practical distances. In the computer program, however, the lens is omitted and the far-field pattern is represented by the direction angles of the scattered rays. The first part of the program generates a diamond and determines its orientation with respect to the set of impinging parallel rays. Owing to the high degree of symmetry of most gems, their shape can be defined by a small number of independent parameters. For instance, in order to describe fully the round brilliant cut, such parameters as the crown angle, pavilion angle, the number of facets, etc, are sufficient. The coordinates of all corners and their correspondence to facets are then determined. A computer drawing of such a diamond, based on the above mentioned parameters, is presented in figure 2. The second part of the program simulates the interaction of light with the gem. In the present work only a set of parallel rays, incident perpendicularly to the table of the brilliant, is considered. Furthermore, we assumed that the illuminating light is natural, i.e. unpolarized [10]. This enabled us to exploit the high symmetry of the problem and to reduce the amount of necessary calculations. The program, however, is capable of dealing with a case in which any direction of orientation is chosen and includes the treatment of diffused light which is represented by many sets of rays having an arbitrary direction of propagation. Each ray, from the incident set, is propagated until it intersects with one of the facets. There it is either reflected or refracted in accordance with Snell's law and Fresnel's formulae†. The reflected part is stored while the refracted ray is continued inside the gem. The simulation of reflections and refractions goes on until the computed

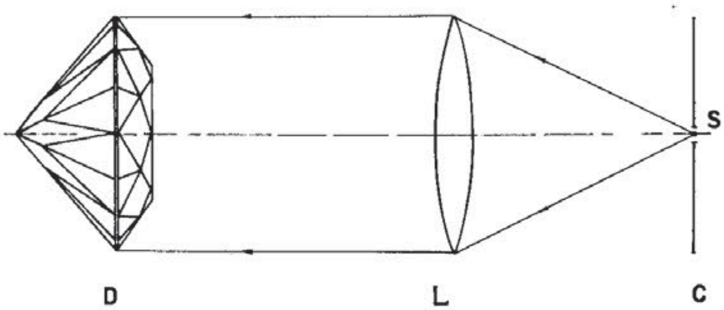

Figure 1. The experimental set-up simulated by the computer program. The light source is indicated by S. SC is a screen, L a converging lens and D the diamond. In the present paper we only consider rays incident perpendicularly to the diamond's table.

† Rigorously, the reflected light is partially polarized even though the incident wave is unpolarized [10]. The effect becomes pronounced only after several reflections but then the ray's intensity is rather low. To simplify the problem and minimize computer time this effect was ignored and the reflectivity at each facet was always assumed to be that of natural light [10].

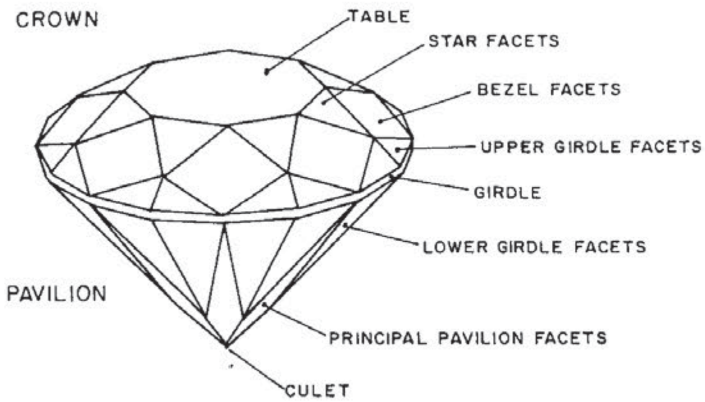

Figure 2. The modern brilliant cut.

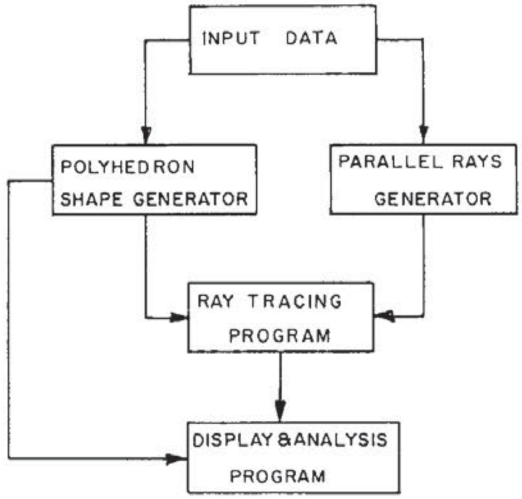

Figure 3. The computer flow-diagram.

intensity of the ray drops below a predetermined value (typically 0·01 of the input intensity). The same process is then repeated with all other rays. Eventually, all scattered rays with the same direction of propagation are grouped together, taking into account their relative intensity, thus producing a far-field pattern which is represented as a spot diagram on a spherical surface. It is worth noting that alternative patterns, indicating the origin of each scattered ray on a facet, can also be obtained. Thus, one can properly take account of the relative visibility of the various facets of the gem. A flow diagram of our program is presented in figure 3.

3. Application of the ray tracing model

Based on the computer ray tracing approach described in the previous section, we concentrate here on a study of various gem cuts. The computed reflection patterns are visually compared to each other and to patterns most widely in use at present. An empirical criterion to characterize the best cut is then conjectured.

In figure 4 we show the effect of pavilion angle variations on the reflection pattern of a brilliant cut. On the right hand side of the figure a projection of the brilliant cut under consideration is shown. On the left, the corresponding reflection pattern is given (within a cone angle of 60°), while the middle column indicates the power flow

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