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Observation and Measurement of the Appearance of Metallic Materials. Part I. Macro Appearance

The use and characterization of metallic paints and plastics have been important, particularly in the automotive industry, throughout the last half of this century. The scientific concepts and terminology of this field are still evolving. The principal appearance characteristics of these materials, when viewed at a distance, are luster and goniochromism. Methods of characterizing and measuring metallic surfaces are being standardized by a committee of the American Society for Testing and Materials. New instrumentation has been developed to provide controlled viewing conditions for judging these materials. Modern portable multi-angle measuring instruments are easy to operate and take measurements very quickly.

Key words: color, metallic, metal-flake, luster, goniochromism, goniochromatism, appearance, goniospectrophotometry, multi-angle spectrophotometry, standardization, viewing conditions

INTRODUCTION

The most popular exterior finish for automobiles is a coating containing metal-flake pigments in a nearly transparent resin. The metal flakes are minute, shiny, thin plates, which tend to lie parallel to the surface of the paint. Such pigments are also dispersed in plastics. Automotive applications are prominent, but these finishes are used elsewhere, notably on sports equipment. These materials are commonly called "metallic" paints or plastics. Their appearance varies with the direction of illumination and viewing.

As early as 1935, Packard Motor Company used paint, made by du Pont, containing fine metal-flake pigments. The paint also contained a large amount of titanium dioxide, which scattered so much light that the flakes were almost hidden. In the late 1940s, the amount of titanium dioxide was reduced to make what would now be called "metallic paints" and these paints were generally introduced in the 1950s.[1] Edwards and Wray described metal pigments and their manufacture, in 1955.[2]

By 1977, about 67% of all cars produced in the U.S.A. had metallic finishes,[3] by 1986 the number had risen to 70%,[4] and by 1987, 80%. In Europe, they rose from 4.8% in 1970 to 54% in 1985.[5]

This article describes ways of viewing and measuring the appearance of these materials, not the theory of light propagation used to predict a colorant formulation to match a given specimen. Colorant formulation is not treated, but some references provide an introduction to the literature.[6–16] Most of the discussion in the present article centers on paints, but is largely applicable to the appearance of plastics. Pearlescent pigments are similar to metal-flake pigments in some ways, but different in others, because they introduce an additional optical phenomenon, thin-film interference. They are not specifically treated here, but the distinction may be academic, because metal and pearlescent pigments may be used together and there are metal flakes treated to appear more like pearlescent flakes. Appearance terminology and the methods of measurement are applicable to all materials.

This article, Part I, pertains to the appearance of these materials viewed from a distance of a few meters—what I call the "macro appearance." When they are viewed at reading distance, about 250 mm, with directional illumination, the individual flakes may become apparent. That is what I call the "micro appearance," the subject of a planned subsequent Part II of this article.

GENERAL TERMINOLOGY

The terminology of this field is still evolving. The refinement of terminology serves science by clarifying concepts and identifying qualities to be described and quantities to be measured.

Metallic finishes have an appearance that automotive stylists sometimes call "glamour." The peculiar appearances produced by metal-flake pigments are loosely called "effects" and the pigments are called "effect pigments." These catch-all terms are too vague and broadly inclusive for a phenomenon of such commercial importance and scientific interest.

The term "metallic," meaning "of, relating to, or being a metal,"[17] is appropriately applied to metallic pigments, but, when it is applied to paints or plastics, it causes confusion even in the field of appearance. I subscribed to an abstract retrieval service to keep abreast of developments in "metallic paints" and was inundated by abstracts describing paints to coat metals. When Hunter announced the Dori–Gon Glossmeter ". . . designed for evaluating metallic and high-gloss finishes," the term "metallic" was used in the dictionary sense.[18] Christie published an article on "An instrument for the geometric attributes of metallic appearance," where he discussed the appearance of metals.[19] The American Society for Testing and Materials (ASTM) lists hundreds of publications under the heading "Metals and metallic materials," practically all of which pertain to metals.[20] In Hunter and Harold's book, *The Measurement of Appearance,* the word "metallic" is almost always used in the dictionary sense.[21] I would prefer the more explicit term "metal-flake" for precise technical discourse, particularly in a context in which there may be ambiguity, but the term "metallic" is so well entrenched in the paint and automotive industries, and in the vocabularies of car salesmen and car buyers that there is no turning back. We are reminded of Lewis Carroll's Humpty Dumpty: "When I use a word, it means just what I choose it to mean—neither more nor less."

If a car is painted a solid light gray and an otherwise identical one is painted metallic "silver" and they are viewed at a distance of several meters or more, with an overcast sky and snow on the ground (or other diffuse illumination), the two may look alike. However, if they are viewed the same way in full sunlight (or other highly directional illumination), there is a striking difference in appearance. The finish appears especially bright in the highlights and darker elsewhere. This makes the curved surfaces look more curvaceous, by which I mean they appear to have a higher degree of curvature. It is surprising that no such meaning is given for "curvaceous" in either *Webster's Dictionary*[17] or the *Oxford English Dictionary.*[22] In fact, the voluminous Oxford doesn't list the word at all. The only definition in Webster is "having a well-proportioned feminine figure marked by pronounced curves: marked by sex appeal."[17] Considering the notorious American male "love affair" with automobiles, perhaps the stylist's term "glamour" is not far off.

In an article on "geometric metamerism," in 1967, Johnston opened with a definition: "Two colors which appear identical when viewed at one angle, but which no longer match if the viewing angle is changed, are called geometric metamers."[23] She attributed the term to Henry Hemmendinger and Hugh Davidson. (She had used the term in her 1966 article on color and appearance.[24]) There was a clear need to identify the concept and emphasize its importance, and her usage was an understandable extension of the term "metamerism," but many felt the meaning should not be extended beyond its established spectral connotation. (Later, standardizing bodies were to adopt this position.) In view of such objections, in 1969, Hemmendinger and Johnston proposed the terms "goniochromatism" for the phenomenon whereby the color of a specimen depends on angular conditions of illumination and viewing. They proposed "goniometachromatic" for a pair of specimens that match under some angular conditions, but not all. They proposed "gonioisochromatic" for a pair of specimens that match under all angular conditions.[25] Of these, only "goniochromatism" has come into widespread use.

Occasionally, the term "polychromatism" has been applied to a change in the color of a specimen with a change in viewing angle.[26,27] This usage suffers from the fact that "polychrome" has, since ancient times, meant an object exhibiting more than two colors, such as a pot with red, yellow, and green decoration.[17] Today a several-color printing process is called a "polychrome process." Rarely, "two-tone" has been used in this connection, but certainly ought not to be employed in the American automobile industry, where it more often has meant the use of two distinctly different colors on a car.

The color observed when the line of sight is along the normal to the surface of the specimen is called the "face" color. The surface is facing the observer. The color observed when the specimen is viewed at a large angle to the normal is called the "flop" color. The specimen may flop from one color to another as it flops from one position to another.

Flake orientation is an important contributor to the appearance of metallic materials. The flake orientation is evident in photomicrographs of paint cross sections, such as one published in 1967 by Johnston.[23] The orientation of flakes is not always isometric with respect to the specimen being rotated in its own plane. The process of forming plastics or spraying a paint on a vertical surface (in the earth's gravitational field) may cause a preferential orientation. This phenomenon has sometimes been called "the venetian-blind effect." Anisometric specimens such as this are said to be "directional."[28]

The names of instruments in this field are ponderous, to say the least. A "goniometer" is a device for measuring angles. A "goniophotometer" measures the amount of light received at various angles. A goniophotometer that has some spectral resolution, such as one equipped with a few colored filters, is called a "spectrogoniophotometer." A spectrophotometer, with spectral resolution adequate for color work, that measures at a range of angles is called a "goniospectrophotometer." The etymological basis is nothing more than the fact that in the English language adjectives come before the noun. An instrument equally suited to measurement of angles and spectra could be called either. A spectrophotometer that measures at a few given angles is called a "multi-angle spectrophotometer." Incidentally, the term "spectrophotometer" is longer than necessary. The simpler term "spectrometer," often applied to instruments to measure wavelengths, can also mean instruments to measure spectral power distributions. This usage deserves encouragement.[29,30,66] The syllable "photo," referring to light, is erroneous when such instruments are used in the ultraviolet and infrared regions of the spectrum.

In almost all cases considered here, the receiver is in the plane defined by the normal to the surface of the specimen and the center of the illuminator. This plane may be called the "illuminator plane."

LUSTER

A special case of goniochromatism of great importance is the case in which the variation in appearance with angle is caused by a variation in the amount of light specularly reflected from first surfaces. The glossy fibers of a lustrous satin are dielectric materials, so the light reflected from the first surfaces is the color of the illuminant, which is taken to be white for appraising appearance. Grained plastics may have surfaces that reflect light in the same way. The reflected white-light affects the lightness and saturation of the color produced by underlying colorants in a characteristic way. The lightness is a maximum and the saturation is a minimum at specular reflections. In such cases, the appearance attribute is generally called "luster." Luster is generally perceived as a property of the surface finish, rather than a "color variation over the surface," even though lightness and saturation are two of the three components of color. But, as Judd emphasized in 1952, perceived surface character and perceived color are often inseparable.[31]

The luster of textiles may be characterized by gonioreflectometry. I have used measuring geometry simulating viewing a textile wrapped around a circular cylinder having its axis in the plane of the illuminator and eye. Measured or viewed as described, satin (oriented properly with respect to warp direction) exhibits a pronounced highlight at and near the specular angle and rapidly diminishing reflection at other angles.[32] Rodrigues published a monochrome photograph of a vertical cylinder, the bottom third painted with flat paint, the middle third with glossy paint, and the top third with metallic paint.[33] The apparent increase in curvature of the section with metallic paint is striking. The appearance of that paint on the cylinder is very similar to the appearance of satin wrapped around a cylinder. They enhance apparent curvature in the same way. Thus, the term "luster" is appropriate to this attribute of metallic materials.

Metals may be given a mirror finish or a lustrous finish. Light reflected from a metal is not always the color of the illuminant. Gold, copper, brass, and bronze impart a characteristic color to the light reflected. That is, what might most appropriately have been called "metallic color," had there been divine guidance in the choice of terms. The lightness is a maximum and the saturation may also be a maximum at specular reflections. The variation of saturation opposite to that observed with dielectrics does not diminish the appearance of luster, so we may conclude that the principal feature of luster is the characteristic high lightness at and near specular reflections.

Specular reflection at the surfaces of submerged flake pigments, observed at and near the specular angle of the specimen surface, affects the general impression of luster. Metallic materials have the peculiar trait of providing a luster from within. The combination of that appearance of luster with the appearance of the high-gloss surface is a visually interesting characteristic of metallic materials, but not unique to them. A metal surface with a lustrous finish and a clear lacquer coat may have this appearance.

GONIOCHROMISM

We may encounter goniochromatism involving a variation of hue as well as lightness and saturation, in a manner not perceptually associated with luster. The light reflected from the metal flakes may be colored by characteristic metal reflection and by pigments in the resin. When the paint is viewed at a large angle from the normal, as commonly happens when a surface curves away from the viewer, the flakes are viewed edgewise, so the colorants in the resin play a greater role. I propose that a specimen that exhibits a color variation with angle that is not perceived as luster be called "goniochromic" and the phenomenon be called "goniochromism."

In textile technology, a cloth that exhibits totally different colors when viewed from different angles is called "changeable."[17] (I would not recommend that term for metallic paints, because it suggests that a finish has a chameleon-like inconstancy or is especially easily repainted.) A changeable taffeta may look green from one angle and red from another. When it is draped, one side of a fold may be green, the other red. The peculiar weave simply presents more green fibers in one direction and more red in the other. If the cloth is made of glossy fibers, it is lustrous. If the fibers are dull, the cloth lacks luster. Many lustrous fabrics are not changeable. Thus, it is easy to find textile examples that show that luster and goniochromism are independent attributes.

Metallic materials are not as well-structured as woven textiles, so it is not so easy to demonstrate the independence of luster and goniochromism, but all who have researched the appearance of metallic materials have recognized two attributes of appearance referred to as "lightness flop" and "color flop," or some such terms. There is enough of a distinction to warrant treating luster and goniochromism as separate attributes of appearance. A designer might want to increase luster but decrease goniochromism, if a hue shift were objectionable.

The three different attributes of macro appearance, gloss, luster, and goniochromism, are often embodied in one finish. There is no appearance like it in nature. No wonder it is fascinating to the eye.

METHODS OF MEASUREMENT

In 1964, Carleton Spencer, an automotive color stylist, described criteria for choosing to match a solid color to one of four different identifiable colors of a metallic material: the dark-limit, the light-limit, the midpoint, or the point of "maximum hue strength."[34] He didn't mention goniochromatism or angles, but he certainly knew that a metallic material had more than one color, was satisfied with identifying four, and had clear ideas about how to cope with them.

Writing about early experiments in metallic colorant formulation in 1965, Hugh Davidson wrote, "As far as we know, nothing has yet been published on the use of instrumental matching and control of metalized colors in paints and plastics. . . . it would seem impossible to fully solve the problem without having measurements at near grazing incidence, as well as at approximately 90° to the sample surface." He then described an empirical approach.[6]

In 1966, McCamy described a unified approach to appearance measurement, refined the basic concepts and terminology, introduced the term "reflectance factor" as distinct from "reflectance," introduced a system of specifying geometry, introduced the conical method of simplifying the description of geometry, and introduced functional notation for compact description of geometric and spectral conditions.[35] This approach was adopted in national and international standards on optical densities used to control color in photography and printing,[36] but had little impact on colorimetry at that time.

In 1967, McDaniel described the selection of colors for cars and said curved panels were used to exhibit the "highlight" and "flop" colors as they would appear on a car. He also noted that in the 1967 model year (cars introduced in the fall of 1966), "Our gold mist . . . sold a resounding 12% of all our cars. . . . gold did not even exist as a category three years ago. . . . The metallic influence contributes mightily to the attractiveness of the color."[37]

James Davidson had a Paint Research Institute Fellowship under the direction of Professor Billmeyer at Rensselaer Polytechnic Institute, to study the appearance of metallized paint films. By December 1967, Davidson had assembled a research goniospectrophotometer and measured the reflectance factor of a metallic painted panel, having a reddish-bronze "face" color and a very dark greenish "flop" or grazing-angle color, at a wide range of angles, for narrow wavelength bands at 505 nm and 643 nm.[38]

A commercial recording goniospectrophotometer, the Trilac™, was introduced by Kollmorgen Color Systems (now Macbeth) in 1968. The announcement said, it "will be of considerable interest to those working with materials designed to change color with varying conditions of illumination and viewing, such as paints and plastics that contain metallic particles."[39] Speaking of this instrument, Ingle said, "The continuum of colors in the appearance of . . . a plastic with metallic as well as chromatic colorants can now be determined. Some function of 'high-light' color and 'non-specular' color might suffice to describe the color-element in their appearance."[40] The commercial demand for the instrument was small, so about 1972, it was discontinued.

The International Colo(u)r Association held its first congress, called "Color 69," in Stockholm, Sweden, June 9–13, 1969. The next four articles described below dealt with metallic appearance.

Billmeyer reviewed geometric aspects of color measurement. He described Davidson's measurements.[38] The results were confirmed by measurements with a Trilac™ goniospectrophotometer. Measurements were consistent with visual observations under directional illumination, but differed significantly from observations with diffuse illumination. He saw a need to standardize viewing conditions for such specimens.[41]

Hemmendinger and Johnston described the Trilac™ goniospectrophotometer and presented measurements of metallic paints, vinyl-coated fabrics, and tricot fabrics, for pairs of specimens that matched at some but not all angles.[25]

Baba reported building a "three-dimensional spectrogoniophotometer" and measuring several kinds of materials, including "metallized paint surfaces." The paints exhibited the typical broadening of the specular envelope.[42]

Felsher and Hanau described the use of "reflective pigments for widened color effects." They described the colors produced by flakes of different metal alloys, the increase in luster achieved by using transparent colored pigments of the same color as the metallic pigment, the adjustment of the color of metallic pigments beyond the usual range for a given alloy by the use of colored pigments, and referred to extreme goniochromatism as an "iridescent multi-colored effect." They described the use of a dull surface, rather than a glossy surface, on a metallic plastic, noting that, ". . . distracting reflections from an automobile dashboard are eliminated, while the metallic lustre, viewed subdued through the dulled surface layer, prevents an unattractive, 'dead' appearance." They gave interesting insights into the effect of flake size and the technology of influencing the orientation of the flakes to improve "brilliance."

They gave a keenly insightful analysis of the state of the art of evaluation of metallic colors. In addition to the three colorimetric parameters needed to specify solid colors (which they also called "non-reflective colors"), metallic colors would require knowing "the amount of specularly reflected light, its angular width of dispersion, and . . . the specularly reflected color."

They suggested the possibility of instrumentation: ". . . sophisticated color analyzing instruments may describe metallic and other reflective colors by a series of spectrophotometric or tri-stimulus readings, at various incident and reflective angles, together with one profile showing continuous and discontinuous variations of reflective intensity."[43]

Bunda et al. compared visual judgments of the colors of metallic specimens to measurements with various geometries and found the best correlation with the illuminator at −30° and the receiver at 15°.[44]

In 1970, James Davidson completed a doctoral thesis entitled "The Color and Appearance of Metallized Paint Films." In addition to observations and measurements mentioned above, he experimented with polarization. When the incident light was polarized in the right direction, the top-surface specular reflection was eliminated, but the goniochromatism was unaffected. When the reflected light was also polarized (with cross-polarization), the bronze color otherwise produced by the flake reflections was completely eliminated, "proving that it is dependent on the specular reflection from the aluminum. . ." He distinguished specimens "with a lightness flop" from those "with a color flop."

He characterized the appearance of metallic paints in a number of ways: (1) a polar plot of spectral reflectance factor as a function of viewing angle, for a given illumination angle, (2) a plot of spectral reflectance factor as a function of wavelength for a given geometry, (3) tristimulus values for a given geometry, (4) isoreflectance angle for a specimen, (5) plots of chromaticity coordinates for illuminating angles from grazing to normal, at viewing angles from grazing to normal, (6) comparison of plots of CIE Y as a function of "the number of degrees from the specular angle" for a given illuminating angle (for which he recommended −30° to −45°), and (7) comparison of plots of CIE Y as a function of viewing angle, for a given illuminating angle. Referring to Y as a function of the angle away from the specular direction, he said data "plotted in this manner most clearly show that the angles of illumination of −30 and −45 degrees completely describe the lightness flop."[26] Measuring colors at various angles away from the specular direction was eventually generally accepted as the method of characterizing metallic materials.

At "Colour 73," the second congress of the International Colour Association, in York, England, July 2–6, 1973, Thielert described the variation in color of colored metallic plastic sheets as a function of the orientation of the sheets in their own plane, i.e., their directionality. He made goniospectrophotometric measurements to find the width of the specular envelope, the spectral reflectance factor as a function of angle about the specular direction at half-height, and determined the orientation of the specimen that minimized the width. The maximum width occurred with an orientation 90° from the orientation for the minimum. The color difference between identical pairs oriented at 90° to one another were visually perceived without difficulty. He concluded that a sheet could be characterized by two measured quantities: (1) the color difference between the specimen and a standard, measured with a conventional 45°/0° spectrophotometer with circumferential illumination; and (2) the color difference measured with a directional 45°/0° instrument, between the colors for minimum and maximum width of the specular envelope.[45]

At "Color 77," the third congress of the International Colour Association, in Troy, New York, July 10–15, 1977, McCamy described a unified approach to appearance measurement.[35] He presented goniophotometric measurements at directions outside the illuminator plane for various textiles, ribbed vinyl, and metallic paints, correlated measurements with appearance as illustrated by photographs, reduced the mass of data by selecting angular scans, and proposed mathematical methods of analysis.[46]

In 1982, the German firm Johne + Reilhofer introduced a multi-angle spectrophotometer. It had eleven different angular geometries, the illuminator and receiver beams being in the illuminator plane. At first, the geometry was specified by illumination and receiver angles relative to the specimen normal, but later by specifying the angular displacement of the receiver from the specular direction or "angle from gloss," as suggested by Davidson.[26] The angles of this kind chosen were 0°, 5°, 15°, 25°, 35°, 45°, 55°, 65°, 75°, 85°, and 90°. It was recommended that at least three angles be used. One combination suggested was 25°, 45°, and 75°. If a fourth angle were used, 90° was recommended. Another combination of four angles found useful was 15°, 35°, 55°, and 75°. The instrument could be used to study the directionality of specimens.

An instrument introduced by Johne + Reilhofer in 1987 provided annular illumination at 25°, 45°, and 70° from the normal direction, with the receiver on the normal. Measuring with this geometry averaged the effect of directionality. The 1982 instrument measured at various angles sequentially; the 1987 instrument called a "multi-geometry system" measured at four angles simultaneously. By adjusting an instrument component, one could measure at 12 different angles, the maximum angle from gloss being about 105°. The spectrophotometric system was a double-beam design with flash source and resolution of 1 nm. The measuring probe was connected by a long flexible cable to an accompanying personal computer. Data were graphically presented as a surface in three-dimensional space, with the reflectance factor plotted vertically and the wavelength and the angle from gloss plotted orthogonally on the horizontal axes.[47]

In 1986, Keane of Gardner/Neotec described an instrument called the "Colorguard System 2000/AFC Automotive Finish Colorimeter™," for measuring solid and metallic paints. The specimen was illuminated at 45° to the normal and reflected light was measured along the normal (face) and at a near grazing angle (flop). The sensor was connected to the colorimetric optics by a fiber-optic cable, to facilitate measurements on large surfaces, and color computations were done by a built-in personal computer.[4]

In 1986, Schmeltzer described goniospectrophotometry of metallic paints to characterize their appearance and to provide a basis for formulation. He measured at angles of 25°, 30°, 45°, and 70° from the specular direction, for various angles of illumination, and reported that the measurements correlated well with visual observations. His data showed that the same results were obtained when the illuminator and receiver are interchanged (principle of reversibility). He differentiated "brightness flop" from "shade flop."[48]

At the Inter-Society Color Council Williamsburg Conference on Appearance, February 8–11, 1987, the following four articles pertained to the measurement of the appearance of metallic materials.

McCamy opened with a review of geometric attributes of appearance. He illustrated the application of psychophysics to appearance with examples from photographic science. He stressed the principle of simulation: the geometric and spectral conditions of measurement must simulate the geometric and spectral conditions of use. He noted the long history of studies of photometric geometry in photography. He described goniophotometry outside the illumination plane that characterized the appearance of different materials, including metallic paints, illustrated by photographs. He introduced gonioreflectometry in which angles are not measured with respect to the center of the sampling aperture but are measured at the center of the entrance pupil of the receiver, simulating angular displacements in the visual field. He called this a "receiver-centered scan" and, for measurement of distinctness of reflected images or luster, compared it to the measurement of an optical spread function. He showed how specimens presented for measurement on a curved mandrel can be characterized by receiver-centered scans. He called for standardization of terminology, notation, methods of measurement, and methods of analysis.[49]

Alman described a study of goniocolorimetry of metallic materials. He modeled variations in color as a function of angle with polynomial equations. He then optimized the measurement of color variation by developing a directional sampling plan to optimally determine the model coefficients and minimize prediction errors of the polynomial model. A set of 36 metallic panels, with various flake types and color pigments, were measured in geometries ranging widely in the difference of receiver direction from the specular direction. Then 12 pairs of panels representing small differences in composition were measured. An additional series of measurements were made for various illumination directions for a fixed receiver direction and for various receiver directions for a fixed illumination direction. Flop perception was scaled visually by magnitude estimates of 13 observers, observing 4 times each. The visual reference scale was 0 for a solid color and 10 for a given panel with moderate flop appearance.

The lightness varied with angle much more than the hue and chroma. He called the angle between the receiver direction and the specular direction the "normalized view angle" (what Rösler had called "angle from gloss"). First-, second-, and third-order polynomial models of CIELAB L^* as a function of angle were derived for the 36 metallic panels. The quadratic models fit the data very much better than linear models, but little was gained by using cubic models. Since three measurement directions are required to specify a quadratic equation, three directions were adopted. The optimum three directions were one near specular (15°), one far from specular (110°), and one intermediate (45°). So long as normalized view angles were used, there was no difference in the three modes of varying angles. A simple regression model for L^*, without regard for variation in hue or chroma, correlated well with the visual scaling. He concluded that color measurement at three selected normalized view angles characterized the appearance.[50]

On the basis of this study, an instrument was made with illumination at 45° to the normal and receiver directions at −30°, 0°, and 65° to the normal, and was used for production control, color development, and process control. The normalized angles for this arrangement were 15°, 45°, and 110°.[51]

Venable described a simple theoretical model for reflectance factor as a function of angle. He assumed two components, a diffuse component resulting from scattering and random internal reflections, and a flake component resulting from single specular reflections from flakes. He concluded that measurements at three angles adequately characterize metallic materials. He said one should be as near the specular direction as instrumentation allows, one should be at more than 60° from the specular direction, and the third should be intermediate. He made measurements with normal incidence and receiver angles of 20°, 40°, and 75°. Given normal incidence, these are also the angles from the specular direction.[52]

Steenhoek described a very versatile and highly automated goniophotometer designed for appearance research.[53]

In 1987, Gerlinger *et al.* described a double-beam Zeiss/Datacolor spectrophotometer with a "metallic measurement head" that measured from 5–70° away from the specular angle. In tests carried on at Audi AG, they found a correlation coefficient above 0.9 between visual judgments of "brilliance" (lightness variation) and the measurements at 25° from the specular direction. For light-colored specimens, they found the data at 70° important. They reported observing directionality. They recommended the use of these two angles and conventional 45°/0° measurements.[5]

In 1988, Steenhoek patented a portable spectrophotometer and method for characterization of metallic materials, employing three angles.[54]

At "Color 89," the 6th Congress of the International Color Association, March 13–17, 1989, in Buenos Aires, Argentina, Hofmeister described the measurement of pearlescent and metallic paints with directional 45°/0° geometry, with the specimen simply tilted at various angles to provide measurements at various angles from the specular direction. He described the various appearance effects obtained by mixing pearlescent and metal-flake pigments.[55]

AMERICAN STANDARDIZATION PROGRAM

The significance of measured values depends on the method of measurement being well specified, and the general interchangeability of data depends on standardization of such specifications. In 1988, I pointed that out to friends in the paint industry and suggested that we pursue standardization of methods of measurement of flake materials in the Committee on Appearance of the American Society for Testing and Materials (ASTM). At the meeting of that committee in January 1989, the Subcommittee on Geometry established a working group on the Measurement of Metallic and Pearlescent Colors. Dr. Allan B. J. Rodrigues of E. I. du Pont de Nemours & Company was named chairman and has energetically pursued standardization since that time. It was agreed that pearlescent materials were more difficult to characterize than metallic materials, because their colors depend not only on the viewing angle relative to the specular angle, but on the angle of illumination relative to the normal. For this reason, we undertook standardization of methods of measuring the appearance of metallic materials first. Dr. Rodrigues has reported ongoing activities to national and international technical societies and has enlisted the cooperation of Dr. Heinz Terstiege, who is involved in a similar standardization program in Germany.[33,60]

The tasks identified were: to develop consistent and useful terminology, to prepare representative specimens for the group to study, to study existing instrument specifications and develop a basis for standardization of specifications, and to design and conduct experiments to establish the correlation between measured values and visual appraisals. The fact that the terminology in general use in this field was inadequate or ill-defined mirrored the fact that many of the basic concepts in this field of appearance were not precisely delineated.

At the outset, it was generally recognized that measurements should be made at several "angles measured with respect to the specular direction", but there was no simple name for such angles. I proposed the term "aspecular angle". I also proposed the noun "gonioappearance" for the appearance of a surface for which the appearance changes notably with changes in the geometry of illumination or viewing, and the adjective "gonioapparent" to denote that quality of appearance. These terms were adopted by the ASTM committee on appearance.

In a concurrent ASTM project, I prepared a draft of a standard on geometric description in the field of appearance measurement, based on work mentioned earlier.[35] It has been customary in goniophotometry to measure angles away from the normal—a convention so well established that there was no need for a special name for such angles. To differentiate them from "aspecular angles," I have called them "anormal angles." Functional notation specifies all geometric parameters that affect measurements. In a limited context, such as the comparison of the general design of instruments, the general notation may be abridged to identify the aspecular angles, for example, without specifying the angular subtenses of illuminators and receivers. In that system, the reflectance factor R measured by a multi-angle spectrophotometer that illuminates at 45° and measures at aspecular angles of 15°, 45°, and 110° can be simply identified as:

$$R(45^\circ\text{: } \underline{15^\circ} \;\&\; \underline{45^\circ} \;\&\; \underline{110^\circ}).$$

This notation saves space and facilitates comparison of geometries of different instruments.

Metallic luster can be perceived by illuminating directionally and viewing the specimen at several angles, which happens automatically if the surface is curved. Alternatively, one might look at a surface from one direction and illuminate it successively or simultaneously from several directions. The first simulates inspection in sunlight, the other, the inspection of a car on a car lot at night, illuminated by a string of incandescent lamps. Both are encountered, but if we consider the sunlight case the "natural" or "normal" case, the principle of simulation would require specimens to be illuminated directionally and measured at several aspecular angles. This implies an instrument with a single illuminator and several receivers or a movable receiver. Receivers for color measurements are much more complex than illuminators and movement of a single receiver prohibits simultaneous measurements, so instrument designers invoke the optical principle of reversibility and use several illuminators and a single receiver. As we have defined "normal" viewing geometry, this last design would be considered "reversed" geometry. The geometry can be described in the same way for either case, if we call the direction that would have been the specular direction, if the receiver had been the source, the "virtual specular direction." This concept is under consideration in the group.

At the meeting of ASTM Committee E12 on appearance, on June 21, 1995, the working group was made a subcommittee, with Dr. Rodrigues as chairman.

CONTROLLED VIEWING CONDITIONS

The characteristic glitter of metallic materials depends on viewing with directional illumination. If a car with such a finish is viewed in diffuse illumination, even on the shadow side of a car otherwise in direct sunlight, the luster and glitter virtually disappear. Since Norman Macbeth's first viewing booth in 1915, colorists have judged materials diffusely illuminated. The ASTM standard practice for visual evaluation of color differences of opaque materials specifies diffuse illumination by "an extended-area source."[56] There is as yet no standard directional illumination.

About 1980, at Macbeth, I designed a viewing booth to simulate illumination in direct sunlight. A small source was to simulate the spectral power distribution of sunlight, about 5500 K, and the approximate angular subtense of the sun. The remainder of the area above was to be a brightly illuminated blue surface to simulate the blue sky. The combined illumination was to simulate CIE Illuminant D65, representing mean daylight. The spectral reflectance factor of the requisite blue surface had previously been computed and blue paint had been formulated for the "blue sky" chip on the Macbeth ColorChecker[R] Color Rendition Chart.[57]

At the request of the ASTM working group, Carroll Conklin of Macbeth completed the design and construction of a prototype of such a booth, for experimental use. It presented a wide range of aspecular angles. A neutral gray scale of color differences (CIELAB L^* differences of 0.5, 1.0, and 2.0), made by the Munsell laboratory at Macbeth, was placed in the field of view, to be used as a comparison standard for visually estimating color differences. The interior of the booth was painted black, to maximize the directionality of the simulated sunlight illumination.[58]

It soon became apparent that color differences seemed smaller in the booth than they did in sunlight. That reminded me of the fact that photographs projected in a darkened room appear of lower contrast than prints of equal contrast viewed in daylight. The extreme contrast of the bright screen against the dark surround establishes an extreme scale of contrast against which the image is judged. When the parts of the viewing equipment within the observers field of view were painted light gray, observations in the booth correlated much better with those in sunlight. The blue-sky simulator introduced some specular reflections, which may have simulated outdoor viewing of the top of an automobile, but not the sides. Observers preferred to make critical judgments without the blue-sky simulator.

At the time these experiments were initiated, the distinction between the micro and macro appearance of metallic materials was known, but its implications were not fully appreciated. In the experiments, color variation with respect to viewing angle, as usually perceived on a macro scale, was being evaluated at reading distance. At that distance, the individual flakes were visible, so the viewer saw two colors at a time, the color of the flakes and the color of the resinous matrix, rather than the average color, as seen from a distance. (The eye doesn't average, but instead, tends to emphasize contrast and form against background.) An optical device can be used to blur the field of view so the average color is seen. Limited experiments have shown this technique to be effective. A solid-colored standard chip that matches so that it disappears against a metallic panel, with blurring, doesn't appear to match without blurring.

Saris *et al.* experimented with quite different viewing conditions. They viewed specimens on an indexed tilting table at eye level, with a large "artificial window" behind the observer. The illuminator was 1.65 m wide and 1.42 m high, equipped with twelve 65-watt fluorescent lamps, with correlated color temperature of 6500 K and color rendering index of 95, providing an illumination of 700 to over 2000 lux at the specimen table. The ambient surfaces beyond the specimen table, providing the surround or background, and that above it, being specularly reflected in tilted specimens, all were black. They found high correlation between visual judgments of color differences and color differences measured at aspecular angles of 25°, 45°, and 110°, computed by the general CMC color difference equation, with l = 1.5 and c = 1.00. They found, at least as a tentative conclusion, that correlation was improved by using a CMC l:c ratio of 3:1 for the low and intermediate angles and 2:3 for grazing angles. (This probably reflects the fact that at low angles the lightness change is dramatic and that at the grazing angle the chroma change is.) Viewing in a conventional viewing booth with diffuse overhead illumination and light gray walls was not nearly as effective.[59]

At first, such a large illuminator would seem inappropriate for observations of an angularly dependent attribute of appearance. Care was taken to avoid seeing a specular reflection of the illuminator, when viewing at the face angle. That required centering the observer's head between the illuminator and specimens. Under these conditions of viewing, the specimens were illuminated annularly, but the angular subtense from the specular direction (the line of sight) was not as large as the size of the illuminator might seem to suggest. The annular illumination simply adds more light than a single directional illuminator at a small angle from specular and averages out any directionality of the specimens. Likewise, the tilted specimens were illuminated within a somewhat restricted range of angles, because they were tilted away from the illuminator. Thus the illuminator was "diffuse," but the illumination was not. (It should be noted that the illuminators and receivers in small measuring instruments necessarily subtend somewhat larger angles than are used in research goniophotometers.) It appears that the observations were made at a distance somewhat greater than that used in the ASTM experiments thus far. It was not reported whether the flake discontinuity or glitter was perceptible at this distance.

METAL-FLAKE MEASUREMENT COMES OF AGE

The Federation for Societies for Coatings Technology has sponsored Symposia on Color and Appearance Instrumentation (SCAI). The symposium in Cleveland, OH, April 25–26, 1990, left no doubt about "the state of the art" of measurement of the appearance of metallic materials. The art had become a science, the science had spawned a branch of engineering, the engineering had brought forth practical methods of measurement, and a number of companies had made instruments readily available. In addition to a series of technical articles, there was an exhibition of commercially available instruments. Both were well attended.[60]

Gerlinger of Zeiss described an instrument with a fiber-optic probe that measured color at aspecular angles near 0°, at 45°, and either of two large angles.

Rösler of Kollmorgen Instruments GmbH described a portable spectrophotometer that measured near 0°, 45°, and two large angles, but could be reconfigured easily to measure at 12 different directions. He demonstrated that measurements are required at more than three angles to characterize some materials.

Begert of Audi reported on organization and instrumentation for managing the colors of plastics and coatings in the automotive industry.

Venable of Hunter presented his model of metallic paints and argued on that basis for the use of an angle near 0°, one near grazing, and one well under 45°. He thought the 45° direction to be less revealing, even though most workers had found it useful and had argued that it provided a link with conventional colorimetry, as recommended by the CIE.

Hofmeister of Merck described the relationship of flake type and colorant formulation to goniocolorimetry.

Rodrigues of du Pont reported on the ASTM working group, and Terstiege of BAM in Berlin reported on the activities of the corresponding BAM-DIN Committee. Terstiege felt the work thus far had not been very fruitful and looked forward to what progress might be made by the ASTM group.

The International Color Association (AIC) held an interim symposium on instrumentation for color measurement, September 3–5, 1990, in Berlin. There were four articles on metallic appearance.

McCamy related colorimetry to visual appraisal and gave the history of the development of standard lighting for assessing appearance, including the sunlight simulator being used by the ASTM group.[61]

Rodrigues reviewed the measurement of metallic and pearlescent colors, particularly the work of Venable,[52] Alman,[50] and Saris *et al.*[59] He also reported a new analysis of the measurement of "high glamour metallics and pearlescents," 18 metallic and 16 pearlescent, at aspecular angles at 5° intervals from 15° to 110°. The data were analyzed by the polynomial modeling method of Alman.[50] The 15°, 45°, 110° geometry was clearly superior to a proposed 20°, 45°, 70° geometry. The first of these had been used for routine color control for eight years. The principal difference in these geometries is at the high angle, and the measurement at 110° may be quite different from that at 70°. (This high angle corresponds to the view of an automobile surface curving away from the observer, which is an essential part of the appearance.) He noted that Saris *et al.* had found that visual appraisals correlated well with measurements employing diffuse illumination and attributed this finding to the fact that the artificial window used didn't provide directional illumination. Though the 45° angle may be a convenient link to CIE geometry, he found that any intermediate angle from around 45–60° correlated well with observations. He found no advantage in measuring at aspecular angles under 15°. He reported that practical tolerances for colorimetric variation are about twice as large for the two extreme angles as they are at 45°. He reported a flop index as a function of CIELAB L^* measured at the three angles, derived by Alman from psychophysical experiments, which may be written:

$$F = \frac{2.69(L_1 - L_3)^{1.11}}{L_2^{0.86}}, \qquad (1)$$

where F is the flop index; L_1 is CIELAB L^*, measured at the aspecular angle of 15°; L_2 is CIELAB L^*, measured at the aspecular angle of 45°; and L_3 is CIELAB L^*, measured at the aspecular angle of 110°.

He described the ASTM test specimens: 44 color difference pairs for nine different paints, including light, dark chromatic, and achromatic colors and including small, medium, large, and round flakes, scattering titanium dioxide, microtitania, and different paint application techniques.

He briefly reviewed multi-angle color measuring instruments available at that time, including the Datacolor GK111 (measured at 11 angles: every 5° from 20–70°), the Datacolor MMK 111 (measured at 3 angles: 25°, 45°, and 70° with optional 20° and 110°), the Macbeth Color-Eye™ 5010 (measured at 12 angles: 0°, 10°, 20°, and every 10° from 35–105°), the Optronic Multiflash™ (measured at 8 angles: 20°, every 10° from 25–75°, and 115°), the Phyma (measured at 5 angles: every 15° from 15–75°), the du Pont MAC (measured at 3 angles: 15°, 45°, and 110°), and the Murakami research goniospectrophotometer with a continuous angular range. Considering the ease with which these instruments could be used to measure colors on a car, he described the best in that regard, the Datacolor and Macbeth instruments, as "transportable" rather than "portable," because they had cables connected to a stationary component. He cited patents not yet commercially exploited.[62,63]

He described the du Pont 3PC, a three-angle portable colorimeter built by du Pont for internal use, as light, compact, operable by a single user, and powered by a battery pack on a shoulder strap. It measured at aspecular angles of 15°, 45°, and 110°, by means of reversed optics and a grating spectrum analyzer.

A study of the painting of automobile body and fender parts on two assembly lines (one automated, the other partly manual), using this instrument, demonstrated that the measurements predicted acceptability, the 15° measurements correlated best with observations (so conventional colorimetry was not as effective), CIE lightness L^* differed between body and fender parts by as much as 8.0, the mean lightnesses were unquestionably different, there was no difference in repeatability on the two lines, and the automated line produced a poorer match to the standard than the partly manual line. Other applications were cited.[33]

Besold of Eckart–Werke described the characterization of the "metallic effect" and related appearance to the optical properties of the flakes. He categorized pigments, noting that metal flakes cause reflection, produce a lightness flop, and contribute to hiding; while pearlescent flakes cause interference, produce a color flop, and are transparent. The "brilliance or sparkle" of metallic paints increased with flake size. He described "lightness flop or two-tone." He considered distinctness-of-image gloss (DOI), lightness, brightness, and whiteness essential features of the "metallic effect." Because of scattering at the edges of flakes, small flakes caused a milky appearance, but larger flakes caused higher brilliance or sparkle. Recently developed round smooth flakes, shown in a photomicrograph, produced outstanding brilliance and brightness. Very large flakes tended to reduce DOI. Fairly coarse flakes in a narrow size range produced high brightness, flop, and DOI. These factors depended on flake orientation, which depended on dispersion, formulation, and method of application. A laser granulometer was usually used to determine particle size distribution. He illustrated the use of a goniospectrometer to measure lightness differences for quality control. He computed DOI from reflectance factors at the 30° gloss angle and those at 0.3° to either side of it.[30]

Rösler of Kollmorgen Instruments GmbH described eight years of field experience with applications of multi-geometry color measurement. He attributed the much-discussed inability to correlate measurements and visual observations to ill-defined and highly variable visual observations. He said it is not enough that buyer and seller use the same viewing conditions, if the conditions are *wrong*. He cited the new Macbeth booth as a solution to that problem. He described the Macbeth CE 5010 (ER50) instrument that usually measures at four aspecular angles: 20°, 45°, 75°, and 105°, but can measure at 10° intervals from 10–105°. The wide variety of angles permits a choice of the geometries best suited to the measurement and control of a particular paint. He presented three-dimensional plots of wavelength, aspecular angle, and reflectance factor of a number of metallic and pearlescent paints and discussed their use in color control. It appeared that three or four geometries were usually adequate, but that in the most complex cases, involving interference effects, as many as ten geometries may be needed to characterize a specimen.[64]

At "Colour 93," the 7th Congress of the International Colour Association, in Budapest, Hungary, June 13–18, 1993, there were some articles on the measurement of metallic materials.

Baba of Murakami reported goniospectrophotometric measurements with 45° illumination and the receiver at aspecular angles at every 5° from 20–110°. He measured metals, Morpho butterfly wings, metallic paints, and textiles.[65]

Döring reported correlating visually estimated and measured color differences on metallic paints. He used a GK 311/M goniospectrometer made by Zeiss, illuminating at 25° and measuring at aspecular angles in 5° increments from 10–110°. The specimens were four series of paint panels from the test set used by DIN Committee FNF, each series including 10–12 panels with variations in lightness, hue, and flop characteristics. Visual judgments were made in a viewing booth like that used by the ASTM group. He found serious differences between instrumental and visual results, particularly at lower aspecular angles.[66]

The accuracy of a measurement can be no better than the method and physical standard used for calibration. Diffusely reflecting white plaques are used as calibration standards for reflectometry. Absolute calibrations of such plaques by standardizing laboratories are usually done with geometric conditions recommended by the CIE for general colorimetry. Fairchild *et al.* studied the reflectance factor of the two most common standard materials as a function of angle, to provide a basis for calibrating goniospectrophotometers.[67]

Since the AIC meeting in Berlin, instrument designers and manufacturers have responded to Rodrigues' call for portable instruments. Macco of OPM-E described a multi-angle dual-beam dispersion-type spectrophotometer with built-in computer and memory.[68] A few more examples, taken from manufacturers' trade literature, illustrate the kinds of instruments and features that became available.

The Minolta model CM-512m1 was a battery-operated multi-angle filter-type spectrophotometer with pulsed-xenon illumination at three angles, only 209 × 153 × 130 mm, and weighing 2000 g without batteries. It measured reflectance factors $R(\underline{25^\circ}\ \&\ \underline{45^\circ}\ \&\ \underline{72.5}{:}\ 45^\circ)$, as recommended by the German standards organization DIN. An otherwise similar model, CM-512m2, measured at angles recommended by du Pont, $R(\underline{15^\circ}\ \&\ \underline{45^\circ}\ \&\ \underline{110^\circ}{:}\ 45^\circ)$, and displayed Alman's flop index. These instruments had an automatic position sensor to assure that the instrument was aligned with the specimen surface, and a temperature sensor to help monitor thermochromism.

The X-Rite MA58 Multi-Angle SpectroPhotometer™ was a filter-type spectrophotometer measuring at 20-nm intervals, with a single tungsten light source and a shutter system and fiber-optic pick-up to measure at three angles, $R(45^\circ{:}\ \underline{25^\circ}\ \&\ \underline{45^\circ}\ \&\ \underline{75^\circ})$. It was only 225 × 116 × 76 mm and weighed 1400 g. The instrument stored up to 100 color measurements and downloaded data into a proprietary Windows™-based software system for color control. The similar X-Rite MA68 Multi-Angle Spectrophotometer measured at five angles: $R(45^\circ{:}\ \underline{15^\circ}\ \&\underline{25^\circ}\ \&\ \underline{45^\circ}\ \&\ \underline{75^\circ}\ \&\ \underline{110^\circ})$ and stored measurement data for 999 samples.

The Zeiss GONIOCOLOR™ was a dual-beam dispersion spectrophotometer with 3-nm wavelength intervals, measuring at four angles, $R(\underline{25^\circ}\ \&\ \underline{45^\circ}\ \&\ \underline{70^\circ}\ \&\ \underline{110^\circ}{:}$

45°). It was only 168 × 174 × 116 mm and weighed under 2400 g, with power supply. It had a full range of color computations and display.

The Macbeth Auto-Eye™ 640 series of portable multi-angle spectrophotometers were holographic diffraction-grating spectrophotometers measuring at 10-nm intervals, with pulsed-xenon CIE D65 daylight illumination at four angles, depending on the model:

Model	Reflectance Factor Measured
640	R(15° & 45° & 75° & 110°: 45°)
641	R(20° & 45° & 75° & 110°: 45°)
642	R(25° & 45° & 75° & 110°: 45°)

The instruments were only 313.4 × 303.5 × 152.4 mm and weighed 2380 g. Measurement time was 0.15 s. Pressure sensors assured that equal force was applied to the supports during measurement. External sensors measured the temperature of the specimen and tagged each measurement with a temperature stamp. Internal temperature sensors indicated when recalibration was necessary. Color computations, tolerancing, and large memory capacity were self-contained. The display graphics were based on readily recognizable icons and the output display text and captions could, at the command of the operator, be in English, German, Italian, Spanish, or French. The accuracy of color measurements depends on photometric accuracy and wavelength accuracy. The wavelength accuracy of these instruments was maintained in the field, by periodic automatic calibration of the wavelength scale, using the natural emission spectrum of the xenon source as a series of wavelength standards. This has been the classic laboratory method of wavelength calibration throughout the history of spectrometry.

MEASURES OF APPEARANCE ATTRIBUTES

The macro appearance attributes of metallic materials, other than the color observed or measured in diffuse illumination, are specular gloss, luster, and goniochromism. Specular gloss is well-known and may be measured by standard procedures.[69]

Luster depends on the variation of lightness with angle. The flop index is a measure of that.[33] Considering the uncertainty of producing representative specimens, the probable precision of visual appraisals, and the lack of standardization of methods of observation and measurement, the following simpler quantity should be a satisfactory measure of perceived luster, for metallic materials:

$$S = 3(L_1 - L_3)/L_2, \qquad (2)$$

where S is the measured luster; L_1 is CIELAB L^* measured at the aspecular angle of 15°; L_2 is CIELAB L^* measured at the aspecular angle of 45°; and L_3 is CIELAB L^* measured at the aspecular angle of 110°.

Lightness variation is the principal component of the appearance of luster, but goniochromism may also involve lightness variations. Luster usually involves a shift in saturation, which is a color variation. Some metals produce colored luster. Thus, it is not obvious how goniochromism can be evaluated separately from luster. In evaluating pearlescent materials, which have more pronounced goniochromism than metallic materials, Baba used the distance between chromaticities on the CIELAB a^*, b^* diagram as a measure of goniochromism.[70] One might have a simple reduction in CIELAB chroma in one case and an equal distance corresponding to a difference in CIELAB hue angle of 180° in another. These cases would look very different. If it takes three or more color measurements to characterize a metallic material, nine or more colorimetric parameters are implied and they may all be necessary to characterize some materials. In other cases, the variation in CIELAB chroma or CIELAB hue angle may be adequate measures of the visual effect. Where matching is concerned, it must be noted that the tolerance for hue differences is less than the tolerance for lightness or saturation. This implies that it is useful to consider differences in terms of CIELAB hue, angle, and chroma.

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