NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 108 MARCH 2015

Technical Report

UDC 669 . 14 - 408 . 2 : 669 . 58 : 535 . 39

Development of Highly Reflective Type Pre-painted Steel Sheet

Taihei KANETO*
Tomoaki HOSOKAWA
Takehiro TAKAHASHI
Michiyasu TAKAHASHI
Kohei UEDA

Abstract

Highly reflective type pre-painted steel sheet was developed to enhance lighting efficiency of lighting fixtures. The key ideas for increasing the reflectivity of a coated film are to arrange the larger gap between refractive indexes of binder resins and pigments in the coated film and to create more surface area of pigments in the film. With well-selected pigments based on a proper refractive index, the higher concentration of the pigments in the film and the thicker film were combined, highly reflective type pre-painted steel sheet reached 92% at diffuse reflectivity, which was larger than a conventional white pre-painted steel sheet by more than 5%. And also, the high end model of a highly reflective type pre-painted steel sheet, which reached 98% at diffuse reflectivity was developed and put to practical use.

1. Introduction

A pre-painted steel sheet (also referred to as "painted steel sheet") is a steel sheet that has been painted in advance in a steel sheet manufacturer prior to processing or installation, and has been introduced in the market by Nippon Steel & Sumitomo Metal Corporation under the trade name of VIEWKOTE™. Pre-painted steel sheets enable the elimination of users' degreasing–painting process, as compared with post-painted ones, paint loss is less and the volatile organic compound (VOC) of the paint is efficiently treated in an overall collective manner in the steel sheet manufacturers. Therefore, the pre-painted steel sheets are also contributing to the reduction of environmentally hazardous substances.

Favored by the growing concern over the preservation of environment as its fair wind, the pre-painted steel sheets with this kind of advantages are now widely used, particularly in their applications to home electric appliances and building materials. Furthermore, in recent years, savings of electricity and energy have become the social subject from the perspective of constructing low-carbon societies, and Nippon Steel & Sumitomo Metal has continued to develop products in the field of pre-painted steel sheets from the novel perspective of "saving energy" since the early time.

Domestically for instance, the highest consumption of 14.2% of the entire house-hold electricity is of refrigerators and is followed by the second highest consumption of 13.4% of lighting fixtures;[1)] therefore, the improvement in the efficiency of lighting fixtures contributes greatly to saving energy. Then, Nippon Steel & Sumitomo Metal developed and started the commercial production of "highly reflective type VIEWKOTE™" in 2003, intending to contribute to the improvement of lighting fixtures with its application to the reflection plates of the fixtures. In this report, the concept of enhancing reflection in "VIEWKOTE™ and ideas for coating film designing are described, and some technical points in developing diffuse reflectivity 92% type and diffuse reflectivity 98% type are introduced.

2. Designing of Highly Reflective Type VIEWKOTE™

2.1 The reflection characteristics of light

The reflection of a light is classified into two as shown in **Fig. 1**; specular reflection and diffuse reflection. The specular reflection is the reflection based on the law of reflection (angle of incidence θi = angle of reflection θr) and is also termed as mirror reflection as it takes place on a well-polished surface like a mirror. On the other hand, the diffuse reflection, which is also termed as irregular reflection, means a case in which an incident light is reflected in multiple directions. Particu-

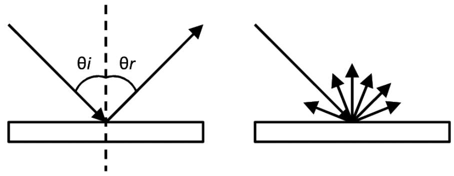

Fig. 1 Specular reflection and diffuse reflection (left: specular, right: diffuse)

* Researcher, Surface Treatment Research Lab., Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

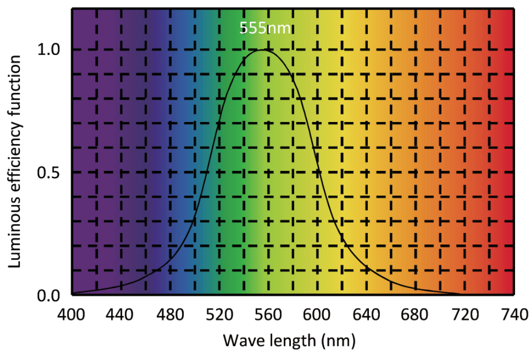

Fig. 2 Luminous efficiency function

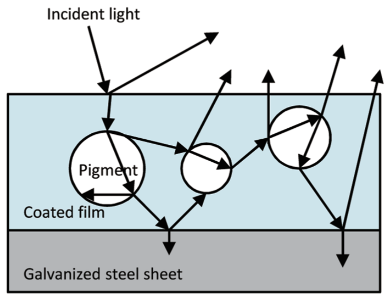

Fig. 3 Light path through coated film

larly when the light is reflected evenly on the reflecting surface in a manner similar to the formation of a hemisphere, the reflection is termed as perfect diffuse reflection. To illuminate an entire subject area, pursuing of the perfect diffuse reflection that makes the reflecting surface luminous in any directions is most suitable.

Luminescence is a human's perception of light that enters a human's eyes and is sensed by the retina being stimulated by the light, and its sensitivity, namely the luminous efficiency that varies according to the individual, is known to be dependent on the wave length of a light. As a mean to express the luminous efficiency objectively and quantitatively, the International Commission on Illumination (CIE) specifies the Standard Luminous Efficiency (also termed as Standard Spectral Luminous Efficiency).[2)] In general, in a well illuminated area, light with the wavelength of 555 nm is sensed as the most luminous, and in the standard luminous efficiency function V(λ) shown in **Fig. 2**, the luminous efficiency at this point is taken as one, and the relative values of the luminous efficiencies of the lights of other wavelengths with the same energy are shown. From Fig. 2, it is known that the luminous efficiency is expressed with a quadric function having its maximum value at the wavelength of 555 nm, and it is known that, to enhance the luminous efficiency of reflected lights, it is effective to pay attention to the light with the wavelength of 555 nm.

2.2 Concept of enhancing reflectivity

Reflection of a light is a phenomenon that takes place on the interface of the substances having different refractive indexes, and from the formula of Fresnel shown below, it is known that the larger the difference in the refractive index between two different substances sharing an interface, the larger the reflectivity R on the interface becomes.[3)]

$$R = \{(n_1 - n_0)/(n_1 + n_0)\}^2$$

where n_1, n_0 are the refractive indexes of the substances

Figure 3 shows the image of the paths of a light that entered a coating film containing dispersed pigment like the one of a pre-painted steel sheet. The light that entered the coating film is separated into two compositions: one that is reflected on the coating film surface and the other that refracts (permeates) into the coating film. The light that permeates into the coating film is separated into the following compositions: the first is the one absorbed by the resin, the second is the one reflected on the interface of the resin and pigment (surface of the pigment), and the third is the one absorbed by the pigment. Furthermore, the light reflected on the pigment repeats reflection and absorption among other pigments and finally, is separated into two compositions: one that goes out of the coating film surface and the other reaching the galvanized steel sheet below the coating film and reflected or absorbed.

From the above, in the designing of the highly reflective type

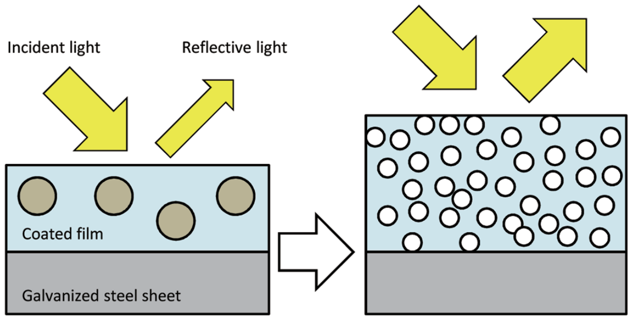

Fig. 4 Images for increasing reflectivity of coated film

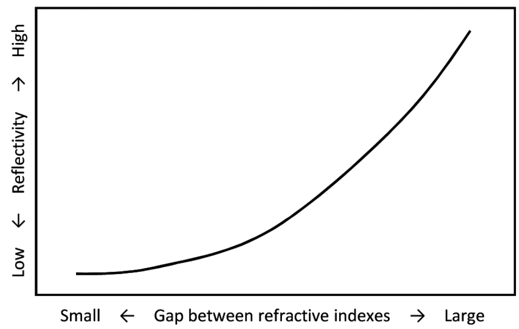

Fig. 5 Relationship between refractive index difference and reflectivity

VIEWKOTE™, it was conceived that reflectivity can be increased by providing larger difference in the refractive index between resin and pigment, and by increasing the surface area of the pigment (**Fig. 4**).

2.3 Selection of pigment excellent in reflectivity

As aforementioned, reflectivity depends on the difference in refractive index between the resin and pigment that constitute the coating film, and the reflectivity increases with the gap between the refractive indexes (**Fig. 5**). The refractive indexes of generally used typical resin and coloring pigment employed in pre-painted steel sheet are shown in **Table 1**.[4)] In the highly reflective type VIEWKOTE™ of Nippon Steel & Sumitomo Metal, the difference in refractive index between resin and pigment is enlarged by employing based pigment TiO_2 (Titania), which has the highest refractive index among all.

Furthermore, when the diameter of the pigment particle decreases, reflectivity increase because the surface of the pigment increase (**Fig. 6**). On the other hand, when the diameter of the particle becomes half or decreases below the wavelength of light, diffusion or diffraction phenomenon of the light takes place and reflectivity shows a downward trend. In general, primary pigment particle diameters are in the range

Table 1 Reflective index of material

	Material	Refractive index
Pigments	TiO_2	2.52
	ZnS	2.35
	ZnO	2.00
	MgO	1.75
	$BaSO_4$	1.64
	$CaCO_3$	1.61
	$CaSO_4$	1.58
Resins	Epoxy	1.61
	Polystyrene	1.59
	Polyester	1.54
	Acrylic	1.53
	Polyethylene	1.51
	Polypropylene	1.49
	Fluoren	1.43
Other	Air	1.00

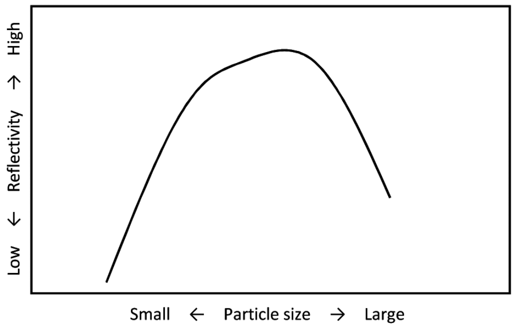

Fig. 6 Relationship between particle size and reflectivity

of 30 nm–30 μm, and many of them stay in the range of 100–1 000 nm[5] and considering that the luminous efficiency of the reflected light is maximum at 555 nm, Titania pigment with average particle diameter of 200–300 nm was applied to the highly reflective type VIEWKOTE™.

2.4 Addition of reflective type pigment to coating film to high degree of concentration

As a method of enlarging the surface of pigment in the coating film, or a method of enlarging the surface area of pigment, there is another method by increasing the concentration of pigment. As **Fig. 7** shows, reflectivity increases with the concentration of Titania in the coating film, and reaches its maximum value near the limit pigment concentration. If pigment is added exceeding the limit pigment concentration, reflectivity decreases as pigment comes in contact with other, reducing the area of interface that reflects lights; however, it is reported that if the concentration of pigment is increased further, reflectivity starts to increase again.[6] This is considered to be due to the fact that the amount of the resin that penetrates into the gap between Titania and pigment decreases and voids (air) having refractive index lower than that of the resin are formed;[7] therefore, reflection also takes place on the interface of air and Titania where the difference in refractive index is larger and the area of reflexing interface is larger.

Differing from post-painted steel sheets that are painted after processing, pre-painted steel sheets are processed after painting; therefore, coating film characteristics, namely coating film workability, that do not develop cracks and/or peeling of coating film in processing are required.[8]

In general, bend performance decreases when the concentration

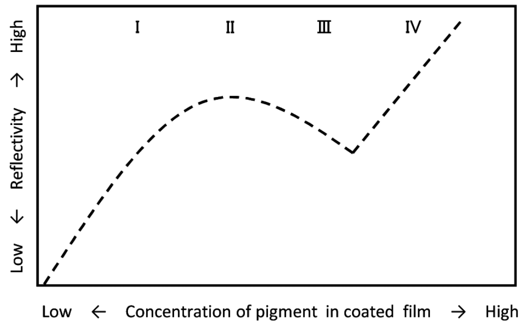

Fig. 7 Relationship between concentration of pigment and reflectivity

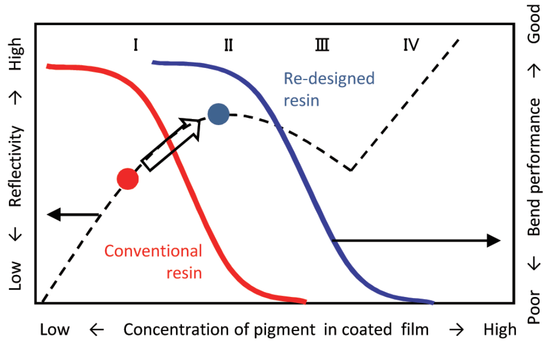

Fig. 8 Influence of concentration of pigment on reflectivity and formability

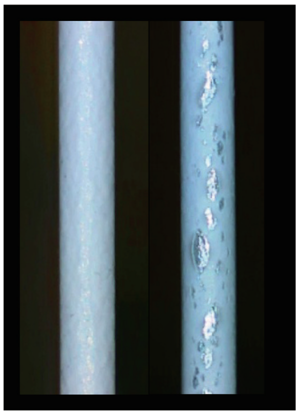

Photo 1 Appearance after bending
(left: highly reflective type, right: conventional type)

of pigment in a coating film exceeds a certain level (**Fig. 8**), the upper limit differs depending on the kind of the resin that constitutes the coating film. Although the resin applied to the white-colored pre-painted steel sheets of conventional type had low pigment concentration for securing bend performance and the sheets were inferior in reflectivity, a new soft resin with high elongation ratio was redesigned for application to highly reflective type VIEWKOTE™ by controlling the molecular weight and the glass transition point of resin. In the diffuse reflectivity 92% type, suppression of cracks at the bent area has become possible near the limit pigment condensation as in the sphere II in the figure (**Photo 1**).

2.5 Increasing coating film thickness

Increasing the coating film thickness wherein pigment is dispersed is effective as a mean to enlarge the surface area of the pigment. Pre-painted steel sheets are produced by coating a thermosetting-type paint on the steel sheet surface and hardening it by rapid heating of within 1 min, where suppression of a coating defect called "blister" becomes a serious technical subject in increasing coating film thickness. Here, a blister is a crater-like defect that appears on the surface of the coating film, caused by the residual volatile compositions like the solvent of the paint becoming unable to pass through the beginning-to-harden coating film surface during the paint hardening process and evaporating in a bumping manner.

Till date, Nippon Steel & Sumitomo Metal has conducted systematic research on the influential factors that cause the generation of blisters,[9] and has employed its results in designing optimum paint. In increasing the coating film thickness of the highly reflective type VIEWKOTE™, the paint was redesigned to allow the extension of fluidity time in paint-hardening by partially replacing the solvent of the paint with a high boiling point solvent so that the blisters generated could be recuperated by the fluidity. With this, the increase of the coating film thickness by 30% or more became successful as compared with that of the white-colored pre-painted steel sheet of the conventional type.

2.6 Reflectivity of highly reflective type VIEWKOTE™

As aforementioned, the crucial issues in the development of highly reflective type VIEWKOTE™ are that the application of Titania based pigment is most appropriate; considering the difference in its refractive index with the resin, it is most efficient when the mean particle diameter is about half of the wavelength of the light of maximum luminous efficiency, and the addition of pigment to its limit pigment concentration, and the designing of coating film and paint that can withstand thicker coating film thickness are important. The diffuse reflectivity of highly reflective type VIEWKOTE™ developed by combining these items reached 92%, higher by 5% than that of the white-colored pre-painted steel sheets of the conventional type. Where, the diffuse reflectivity discussed in this article is the values measured at the wavelength of 555 nm using the Shimadzu Corporation UV-3100 PC.

3. Further Improvement in Reflectivity—Development of High End Model

In the plastic film industry, highly reflective film containing a number of flat voids formed inside, with a film thickness of about ten times of that of the conventional pre-painted steel sheets, and having the diffuse reflectivity of 97% or higher is in the marketplace.[10]

Then, as the high end model of highly reflective type VIEWKOTE™ having a diffuse reflectivity compatible to that of highly reflective film, diffuse reflectivity 98% type was developed (**Fig. 9**) and commercial production started in 2010. The diffuse reflectivity 98% type has been completed to satisfy the specifications to withstand practical use, as the workability of it achieved the level of one R in the evaluation in terms of minimum limit value of R in 90° bending test, wherein the coating film damage or peeling is secured.

The highly reflective type VIEWKOTE™ of diffuse reflectivity 98% was realized by the following two points: to increase pigment concentration in the coating film to reach the high concentration sphere where the pigment forms voids (Sphere IV in Fig. 7), and to increase coating thickness further. **Photo 2** shows a cross-sectional image, taken by a scanning electron microscope (SEM), of the coating film added with pigment to ultra-high concentration. From Photo 2, the state of formed voids in addition to the resin and the pigment in the coating film are observed.

In the paint with pigment added to an ultra-high concentration, the upper limit of the coating film thickness that develops aforementioned blister is eased and the condition is advantageous for increasing the coating film. This is because the residual volatile composition can more easily go through the coating film surface that is beginning to harden by way of the pigment interface and the voids as its paths.

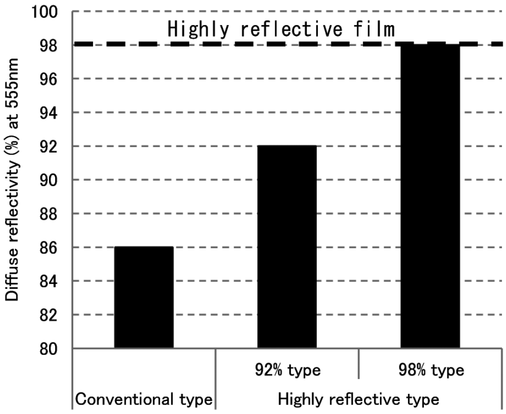

Fig. 9 Diffuse reflectivity of pre-painted steel sheet

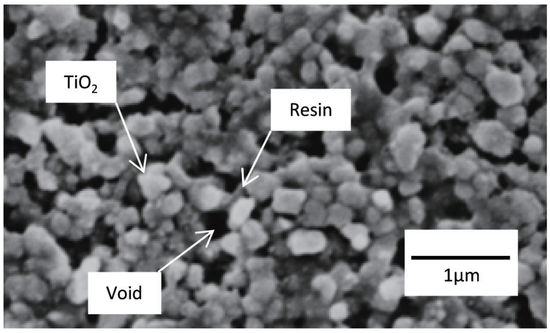

Photo 2 Cross-sectional SEM images of coated film with super high concentration of TiO_2

On the other hand, in the roll-coater method that is generally used in the production of pre-painted steel sheets, uniform coating is difficult for paint with ultra-high concentration pigment. Even though coated, the resulting coating film is fragile, and the film itself is hard to keep the status.

Nippon Steel & Sumitomo Metal has ambitiously tackled the development of production processes, e.g., the development and the practical application of "Roller curtain flow coater.[11] In the development of highly reflective type VIEWKOTE™ with the diffuse reflectivity of 98%, not limiting designing to only coating film and paint, an overall mercantile designing was conducted, including the production process, and this enabled the realization of application to practical use.

4. Conclusion

In this report, the concept of further enhancing reflectivity in the development of highly reflective type VIEWKOTE™ that contributes to the improvement of efficiency of lighting fixtures and points to be considered in coating film designing are outlined. For enhancing reflectivity, it is important to enlarge the difference in the refractive index between the resin that constitutes the coating film and the pigment added to the coating film, and to increase the surface area of the pigment in the coating film.

Accordingly, the important aspects of the technical issues are the selection of pigment, with due consideration to the difference in refractive index with the resin, and setting of the particle diameter. Furthermore, as a mean to enhance the surface area of the pigment, addition of pigment up to the limit pigment concentration and increase in coating film thickness are also very effective, and technical ideas in this regard for realization have also been stated.

The highly reflective type VIEWKOTE™ thus developed has achieved the diffuse reflectivity of as high as 92%, higher by 5% than that of the white-colored pre-coated steel sheets of conventional type. Furthermore, by adding pigment to the coating film beyond the limit pigment concentration, and then, by forming a number of voids in the film, having larger refractive index difference with the pigment, and by further increasing the coating film thickness, a high end model with the diffuse reflectivity of 98% has been developed and put into practical use.

The highly reflective type VIEWKOTE™ has a strong advantage of being a structural member incorporated with high reflectivity, and by applying it not only to the reflective panels of lighting fixtures but also to wall materials and ceiling boards, as shown in the room model of **Photo 3**, it can contribute to the improvement of the efficiency of lighting fixtures. It is a mercantile expected for applications in a wider range in future.

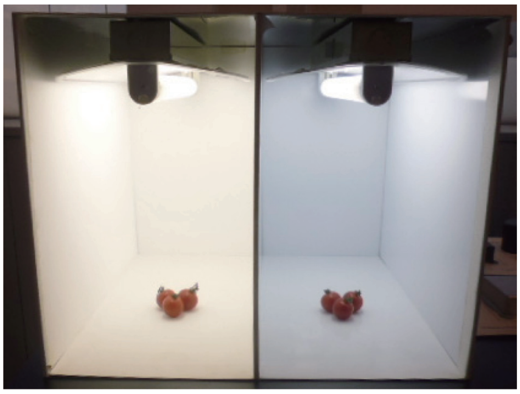

Photo 3 Miniature room model made of pre-painted steel sheets (left: highly reflective type, right: conventional type)

References

1) Ministry of the Environment, Ministry of Economy, Trade and Industry: Future Plan of Lighting (Akari Mirai Keikaku); www.challenge25.go.jp/akari/about/index.html
2) CIE (1924): Luminous efficiency Functions. 1924
3) Ueki, K.: A Guide to Paint Physical Properties (Toryoubussei Nyuumon). RIKO Publishing Corporation, p. 192
4) For example, Coloring Material Technology Handbook (Shikizai Kougaku Handbook)—Refractive Index and Hiding Power of Pigment (Ganryou no Kussetsu Ritsu to Inpeiryoku)
5) Nobuoka, S.: Journal of the Japan Society of Colour Material. 55 (10), 759 (1982)
6) Hosokawa, T. Ueda, K. Takahashi, T.: CAMP-ISIJ. 22, 1409 (2009)
7) Stieg, F.B.: I & EC Prd. Res. Dev. 34, 1065 (1974)
8) JIS K 5600-5-1: Testing Methods for Paints—Part 5: Mechanical Property of Film—Section 1: Bend test
9) Furukawa, H.: Japan Coating Technology Association Meeting for Reading Research Papers, Lecture Proceeding (Toryou—Tosou Kennkyuu Happyoukai Kouenn Yokoushu). 25, 2010, p.11
10) Ide, F.: Trend in Development of Optical Film for Display (Display You Kougaku Film no Kaihatsu Doukou). CMC Publishing Co., Ltd., p.129
11) Kanai, H.: Coating Technology (Tosougijutsu). 43 (13), 65 (2004)

Taihei KANETO
Researcher
Surface Treatment Research Lab.
Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

Kohei UEDA
Senior Researcher, Dr.Eng.
Kimitsu R&D Lab.

Michiyasu TAKAHASHI
Senior Researcher
Surface Treatment Research Lab.
Steel Research Laboratories

Takehiro TAKAHASHI
Senior Researcher
Hirohata R&D Lab.

Tomoaki HOSOKAWA
Manager
Coating Technical Dept.
Sheet & Coil Div.
Kimitsu Works