There is huge demand for automobiles that have metallic finishes. Plastic parts are often painted or electroplated for this purpose. Metallic effect pigments constitute an alternative. Audi and PEG are working on a simulation process for these pigments with a view to ruling out surface defects.
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Simulating Surface Defects in Parts Using Effect Pigments

Effective Prediction

Effect pigments can be used to injection mold thermoplastic parts with a shiny metallic surface. As electroplating and painting are eliminated, the savings potential is huge. However, non-uniform pigment orientation during production can lead to optical defects on the part's surface. Using a suitable simulation methodology enables such surface defects to be predicted and prevented.

Various surface-finishing processes, such as electroplating and painting, are used to give plastic automotive parts a metallic appearance. As a rule, however, these processes are cost-intensive and make subsequent recycling difficult. The use of metallic effect pigments for automotive parts therefore offers substantial advantages in terms of both economy and sustainability. Mold-in-color (MIC) is a technology in which the effect pigments are added to the pellets. These are then injection molded to produce parts that have a shiny metallic surface. At Audi, this technology is employed for bumper parts, for example (**Fig. 1**).

The challenge posed by this technology is how to avoid optical defects on the part's surface. These stem from the orientation imposed on the metallic effect pigments by the manufacturing process (**Fig. 2**). Non-uniform pigment orientation gives rise to differences in light reflection. Parts having areas where there are flow lines and weld lines usually show up dark. The scope for influencing pigment orientation and the resulting defects via the process parameters is limited. This makes it all the more important for the part's design and the mold concept to be optimized early in the vehicle development process.

New Simulation Method Developed in a Collaborative Project

One problem, however, is that a simulation methodology capable of predicting pigment orientation and thus defects does not as yet exist. So, Audi, the Plastics Engineering Group (PEG), and Darmstadt Technical University, Germany, are collaborating on developing such a method. This involves simulating the injection molding process with the aid of Moldflow Insight software from Autodesk.

If the surfaces of the effect pigments are aligned parallel with the part's surface, it may be assumed that light reflec-

Fig. 1. Audi uses metallic effect pigments for the shiny metallic surfaces of various parts in its vehicles. They are found, for example, in the skid plate of the A4 Allroad. © Audi

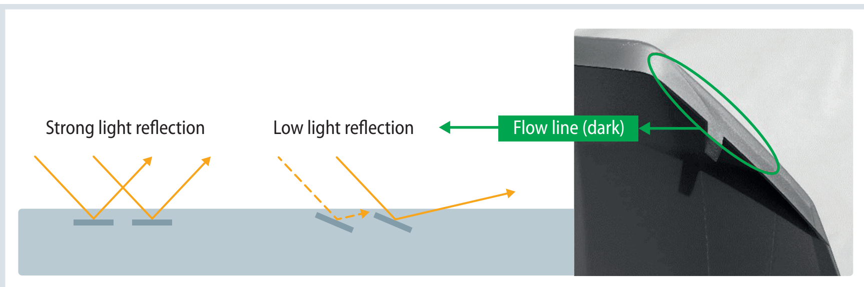

Fig. 2. Schematic diagram of pigment orientation in one area without a defect (left) and in one area that already has a flow line (right): the orientation of the pigments gives rise to differential light reflection, creating the impression of a surface defect. Source: Audi; graphic: © Hanser

tion is uninterrupted. However, if they are disposed at an unknown angle to the surface, the likelihood is that the reflected light will be interrupted and that an optical defect exists. Program implementation is based on calculating a differential angle between the surfaces of the effect pigments (flake normals) and the part's surface (element normals) and thus affording a way of evaluating possible optical defects via a differential angle (**Fig. 3**). The basic procedure is divided into three steps:

- Generation of the CAD geometry to be studied.
- Design and execution of the injection molding simulation using orientation, calculation and adjusted aspect ratio.
- External defect simulation and re-import into Moldflow for graphical evaluation.

The approach will utilize the fiber-orientation models contained in Autodesk Moldflow Insight and the results which they generate will be evaluated in downstream postprocessing. All fiber-orientation models in Autodesk Moldflow have free parameters for adapting simulation results to, for example, experimental results. The fiber-orientation models that are available reveal the scientific advances that have been made in this area:

- The **Folgar-Tucker model** (FT) [1] and the introduction of second-order tensors to describe orientation distributions [2] present the user with two model parameters in Moldflow. These are, on one hand, the aspect ratio and, on the other, the interaction coefficient, which describes the interaction of filler particles with each other.
- The **Reduced Strain Closure model** (RSC) [3], which was expanded with a further parameter to account for the slower orientation kinetics in the edge region, provides a total of three parameters.
- The current standard model, the **Moldflow Rotational Diffusion** (MRD), offers three new coefficients instead of the coefficient.

In all these models, the orientation distribution through the part wall thickness can be influenced via the model coefficients. By contrast, the aspect ratio describes the geometry of the particles contained in the polymer. Here, L is the length of an ellipsoid and D is its diameter (**Fig. 4**). The usual use case for orientation models provides for an aspect ratio of between 10 and 40. As a result, the ellipsoid starts to approximate a chopped glass fiber in shape. If the aspect ratio is set to a value much smaller than 1, the original long half-axis becomes very short, relative to the diameter. The ellipsoid becomes flatter and it starts to resemble a platelet in shape. From the data supplied by the manufacturer of the effect pigments employed at Audi, a mean aspect ratio of 0.001 was calculated and used in all the simulations.

Parameter studies also carried out on simple plate geometry revealed that the RSC model is capable of yielding the best results. As already mentioned, the outcome of a Moldflow simulation is a second-order orientation tensor that describes the orientation distribution of the flakes in the part. This orientation tensor is used to determine the differential angle between flake and surface normal. At the moment, the study is only addressing the uppermost element layer of the injection molding simulation model. The extent to which deeper-lying flakes contribute to defect formation is unclear and is currently being examined. »

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References & Digital Version

You can find the list of references and a PDF file of the article at *www.kunststoffe-international.com/archive*

German Version

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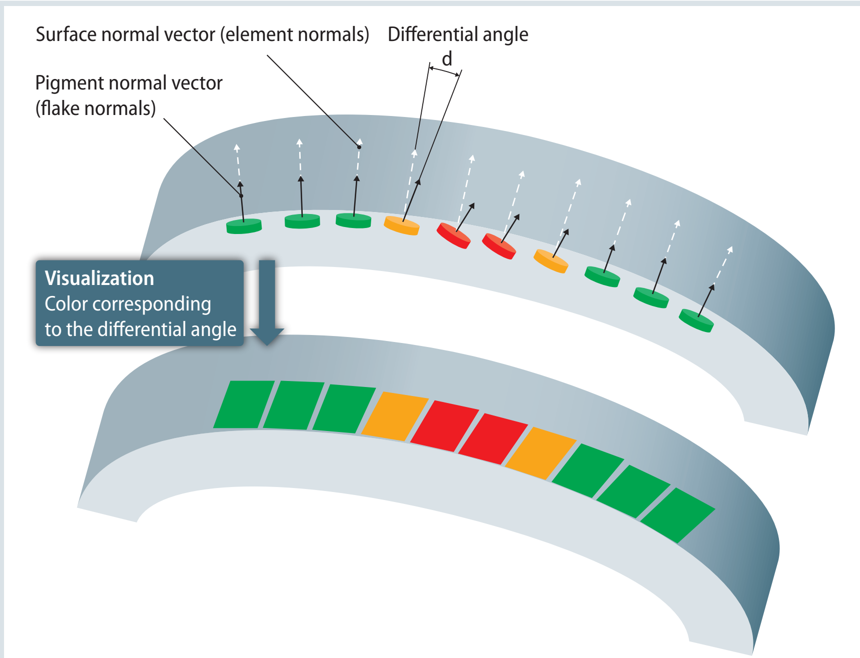

Fig. 3. In the simulation, the orientations of the various pigments are predicted and the differential angle between their surfaces and the part's surface is calculated. This information is used to predict possible defects. Source: Audi; graphic: © Hanser

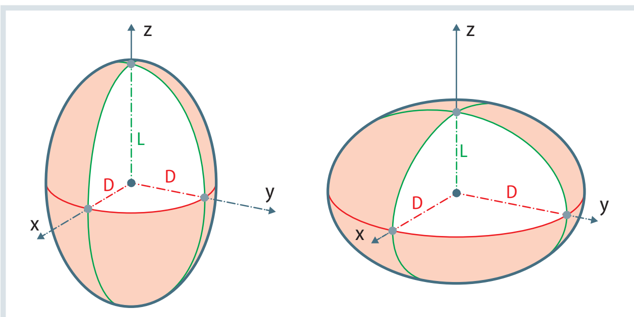

Fig. 4. The shape of the simulated pigment varies with the chosen aspect ratio. Source: [4]; graphic: © Hanser

Differential Angle Calculation: What Is Needed for This

Two vectors are required for the calculation of the differential angle under the planned methodology. First, those elements of the injection molding mesh on the part's surface which have three nodes are identified and are therefore deemed surface elements. For that side of the elements lying between the three identified nodes, the normal vector is calculated. Once this first step is complete, all element numbers for the surface elements and the corresponding normal vectors are now available.

For the identified surface elements, the second-order orientation tensors, calculated from the Moldflow simulations, are also known. As the orientation tensor is expressed in terms of the part's coordinate system, a transformation into the principal axis system must be applied before it can be used (for information about the properties of second-order orientation tensors, see [2]). It can be deduced that the eigenvalues of the tensor describe the degree of orientation and the associated eigenvectors describe the corresponding direction. Initial results visualizing just the calculated differential angle between surface normal and eigenvector (**Fig. 5**) reveal very small differences between the two. Multiplying the differential angle by the corresponding eigenvalue markedly improves the quality of the visualization.

The aim of the experimental study is to validate the methodology on a complex part geometry under the boundary conditions of series production. To this end, a part measuring 400 mm x 375 mm was selected that contains different design elements, such as wall thickness variations, ribs, snap-in hooks, breakthroughs and weld domes (**Fig. 6**). These influence the filling process and thus pose a challenge for the use of MIC material. Gating is done centrally on the top of the part, with Rotec Acrylic PMMA Compound AC-MA 50001 (manufacturer: Romira) being used in addition to the polypropylene (PP) Hifax TYC 459P (manufacturer: LyondellBasell). Preliminary tests had shown that the occurrence of surface defects depended substantially on the injection speed. High injection speeds improve part quality. Fewer flow lines are produced. For this reason, the injection time was varied in several steps during the study (**Table 1**).

Defects Can Be Reliably Predicted

To evaluate the quality of the method's predictions, the results of the simulation were compared with those of experimental studies (**Fig. 7**). For more-accurate defect evaluation, three characteristic sections of the part were examined in detail. In one section of the part, the wall thickness in some areas was reduced (**Fig. 8, top**). These areas show clearly visible optical defects in the form of dark flow lines. The simulation result, too, reveals marked color variation in these areas. The presence of a defect and the area of the defect can be predicted with good accuracy.

	PP	PMMA compound
Base wall thickness	3 mm	3 mm
Mold temperature	55 °C	80 °C
Melt temperature	250 °C	260 °C
Injection times T_e	0.8 s; 1 s; 2 s; 3 s	2 s; 3 s; 4 s
Holding pressure	400 bar (profile)	400 bar (profile)
Number of parts	10 parts per T_e	10 parts per T_e

Table 1. Test parameters for the two materials used. Source: Audi

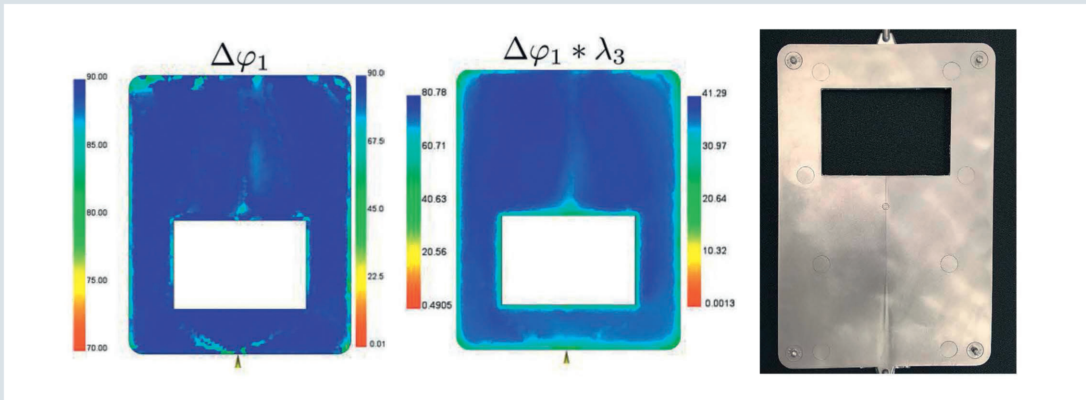

Fig. 5. Differential angle (left) and scaling of the differential angle via eigenvalue (right): the latter leads to much better visualization. Source: [4]

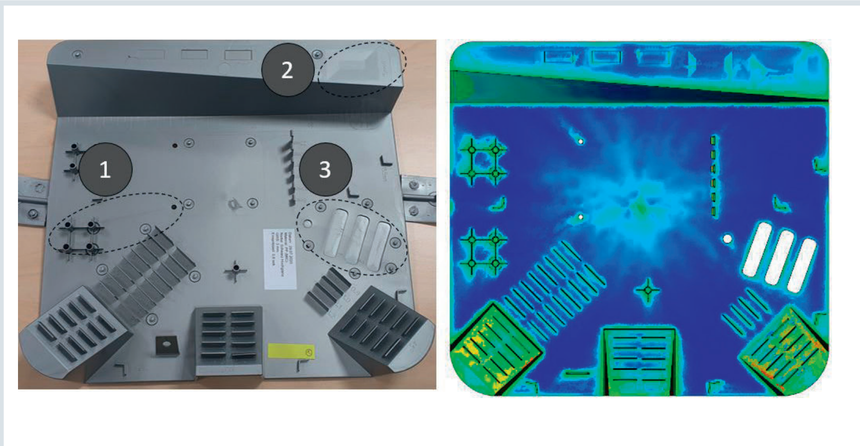

Fig. 7. Comparison between experiment and simulation for the entire part. Source: [4].

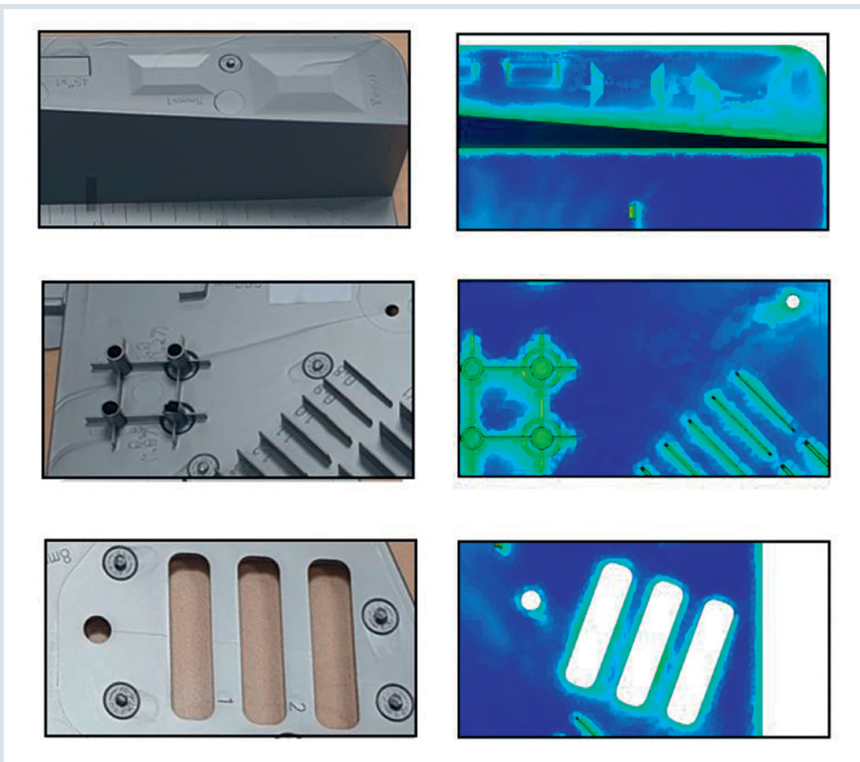

Fig. 8. Comparison between experiment and simulation in three detailed views: flow lines at wall-thickness variations (top), flow lines after weld domes (center), weld line after breakthroughs (bottom). All three examples illustrate the simulation's accuracy at predicting defects. However, when it comes to predicting the exact position and shape of the defects, the methodology still needs to be improved. Source: [4]

However, the length and the exact path of the flow line cannot be evaluated in the simulation.

The simulation is also able, with an acceptable degree of fuzziness, to localize defects in those areas of the part that feature weld domes and breakthroughs (**Fig. 8, center and bottom**). A breakthrough in a part (experiment) is always followed by a fine, dark weld line whose path usually extends as far as the edge of the part (the end of the flow path). In the simulation, a breakthrough is followed by a marked color variation. Thus, the existence of a defect can be correctly predicted. The direction of the flow line can usually be determined, too. However, the extent of the defect in terms of manifestation, thickness and length of the flow line cannot always be clearly determined. In the region of the weld domes, the existence of defects is correctly predicted if the orientation distribution is examined. However, the exact position and the path of the defects cannot be visualized here either. The simulation tends to predict slightly more defects than are found on the actual part.

Overall, the methodology possesses great potential for predicting defects that is open to further optimization. One promising approach might be to calculate and visualize the gradient of the differential angle. The rationale for this is that, when the differential angle changes slowly and continuously, the color change is not perceived as a defect. An abrupt change, on the other hand, is clearly perceptible and should be amenable to visualization via the gradient, in particular. ■