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Laser Nano-Structuring: Adding Colors or Trapping Light

or: The Wind of Light

We don't see light through the air; we can only see the obstacles it encounters. In fact, our perception is all about collisions. Our vision itself begins with collision on the surface of our eyes and ends with the mind construct we call reality. Let's then play with the nanostructure of the surfaces. This article will briefly describe the major steps in developing a machine using laser to structure 3-D surfaces and then present the different attempts in adding colors by light by reflection as well as light trapping.

We can't see the light through the air; we can only see the obstacles it collides with.

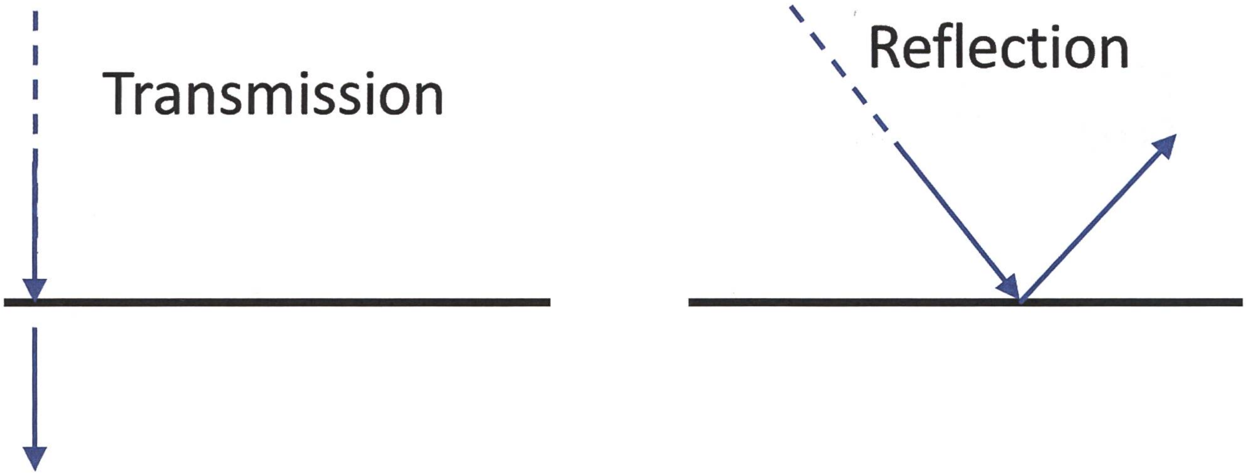
In fact, each of our perceptions is related to collisions. Obviously, experiencing the softness of a rose petal is the collision between our skin and the flower, smelling its perfume is the chemical reaction between its components and some of our nose-specific cells, and the same goes for our sense of taste. Sound is a vibration transmitted to our small dancing ear bones. Perception is when a collision turns into an encounter.

Our experience with light is a sequence of collisions. Our vision starts with photons colliding with our eyes' light sensors, rods and cones, and ends with the mind construct that we call reality, the encounter between our self-created image and our consciousness.

Even if this article is based on science and experience, light and colors involve a large part of subjectivity. We are not simply observers, we are not outside the experience; we are fully involved, and, I dare say, we influence it. I will come back to this aspect at the end of this exposé.

It's all about collision

It is all about collision, so let's "see" what happens when light encounters an obstacle, what the relevant factors are, and first what the different types of interaction are. Basically, photons will either bounce off the obstacle or get absorbed, or a combination of the two. Light bouncing off will be reflected as on a mirror surface, while light being absorbed will be transmitted as through the glass of a window. These interactions will depend on the type of material, its chemical structure (steel, stone, pigments), and the tribology of its surface. This article will focus mainly on metallic materials and first presents the applications that customers can realize with our laser-based machines.



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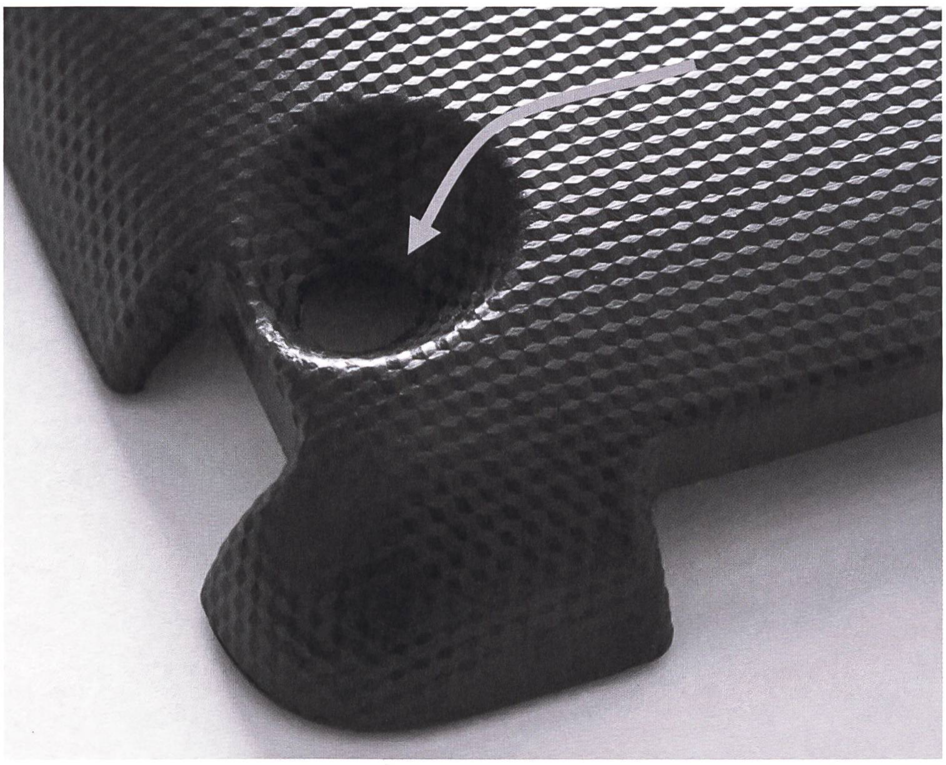
Texturing and structuring laser machines

We have developed a full range of machines to texture molds for automotive interiors, for tires or for ICT (Information & Communication Technology) equipment such as phones and tablets. Our first target was to offer wider possibilities of decoration to designers than the eco-unfriendly etching process could achieve. The customer can create any pattern, map it on any shape – helped by a powerful software –, and our machine will engrave the mold surface, layer by layer. This new technology is fully digital: on the one hand, quality does not depend as much on worker skills as in the etching process and on the other hand, there are tremendous advantages for customers. Firstly, they can obtain a realistic rendering of each texture on their screen before machining the expensive tools to produce the parts. Secondly, they can easily compare the visual effect of the different patterns. Thirdly, they can adapt the way the texture is mapped on the surface and the way it is stretched or shrunken. All these benefits are obtained by a simple stroke of the mouse. Doing so, they save money and time by preventing reworking and avoiding human errors. In addition, this technology gains them access to more complex patterns, giving them an added edge over the competition.

Our traditional business partners were mold makers, but thanks to this technology breakthrough, we gained access to decision-makers in the car industry as well as to plastic injection makers. We learned a lot from the customers (plastic injection companies) of our customers (mold makers), in particular about plastic injection challenges, most of them related to the micro-nano surface character-



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1 Photons either bounce off or are absorbed by the obstacle.

2 Matching texture on shape.

協

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力 power or man

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istics of the mold. The main challenge is adhesion capability: injected plastic might stick on mold surface, thus requiring significant maintenance. We started to collaborate with Dupont™ (one of the major plastic suppliers) and their laboratory, where they were able to measure injection forces. Our goal was to investigate what we could do in terms of surface tribology, which would reduce demolding forces and also allow us to prevent scratches on the finished part. This is what pushed us into developing so-called finishing strategies, not knowing that we were just entering a much wider field than decoration texturing: functional surface structuring.

Functional surfaces

Improving the injection process by structuring the "skin" of the mold was just a first step. More and more ideas came to us, and we received an increasing number of requests for surface functionalities such as surfaces that reduce or increase friction forces, reduce or increase wettability, anti-icing, anti-bacterial and self-cleaning surfaces, accelerate osseo-integration, the ability to trap or to diffract light. Some of these characteristics are still beyond our reach but others are just waiting for our technology to be realized.

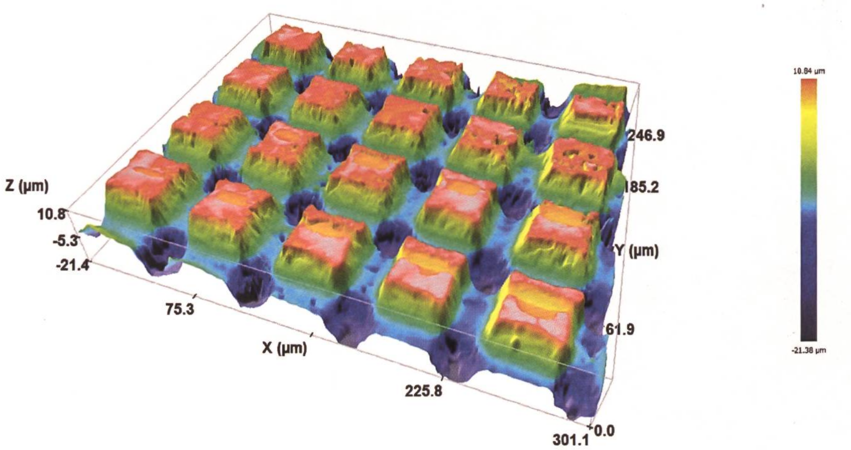
In order to meet these requests, we had to deal with several important issues. The first one was to know what functional effect each surface structure had. Such knowledge is still largely at the research stage in certain universities. The second issue was to be able to see the surface structures – we are speaking here about details whose size is thirty to a hundred times smaller than the diameter of a human hair. And not only to see, but to measure, to find ratios describing their characteristics, and, if possible, to correlate with roughness, brightness, randomness ... The third issue was that most of these surface structures are micro- or even nano-size, so how can a laser beam, with a spot diameter of 30 µm, engrave smaller details than its own size.

Working with institutes

It has not been difficult to find institutes to work with. In fact, we had to select from the numerous requests we received from universities worldwide willing to work on technical surfaces. The selection was easy too, primarily based on the number of publications in this domain but also on our wish to have, for each surface, a customer with a specific expectation. At this point, I'd like to explain my own view on how to make sure that research leads to results that can quickly be used in an industrial process or product. When tackling a technical issue, my request is to work as a triumvirate, similar to the one which founded Switzerland, in other words, three representatives willing to join forces and collaborate together. Our country has now existed for more than 900 years. I recognize that such an "extrapolation" might sound strange, so I will also refer to the way Japanese people write "cooperation": cooperation is the combination of three times the symbol of "power" and one time the symbol of "tree". In other words: three people are needed to cut a tree. In our innovation process, "being three" means that there is one to take care of *what* surface will provide the functionality (the institute), one to define *for what* use the functionality is needed (the customer) and one to take care of *how* to realize it (us). It is similar to "design thinking": technical feasibility and economic viability are important, but desirability is a must.

Measuring surface characteristics

We decided to acquire sophisticated equipment to scan surfaces at a nano-level. Such systems are based on different technologies – confocal, auto-focus, interferometry –,



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3 Japanese characters for "cooperation": three times the symbol of "power" and one time the symbol of "tree".

4 Surface measuring at the nano-level: the altitude of each point is shown via a color scale.

5 Every small square, on the part shown here, is the result of a specific scanning speed on a vertical axis (the higher the speed, the lower the energy per surface [fluence]) and a frequency (the higher the frequency, the higher the fluence). On the left top side, fluence is almost not sufficient enough to have an effect and, opposite, on right bottom side, fluence is high enough to start ablation, and the coloring effect disappears.

6 Diffraction of light. The direction of the beams depends on the spacing of the grating "pattern size" and the wave length of the light.

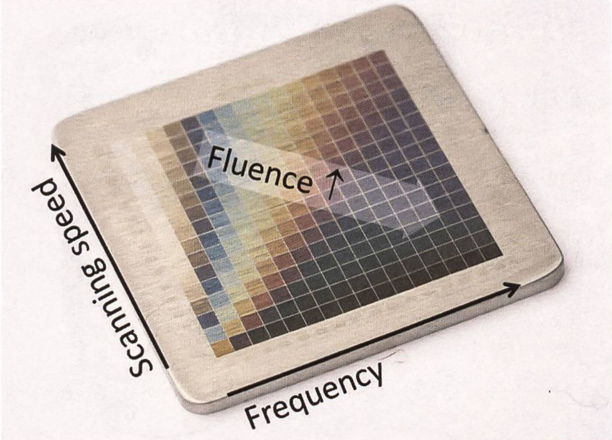
which would take too long to explain here. It is just important to know that each of them has its advantages and its drawbacks, and that combinations may sometimes be required. In a nutshell, the system of the scanning equipment works with a microscope that displays a magnification of the surface. We quickly understood that such images were difficult to read. Just imagine them as a picture of the surface of the moon where the craters have been made by laser sublimation instead of by the collision of an asteroid.

Even though these systems provide a view in which the altitude of each point is shown via a color scale, it is not easy to interpret such images. Fortunately, these scanners calculate different ratios, maximum height, average depth, and some of them happened to be quite relevant to our surface characterization, but not yet easy to correlate with the functionalities we were aiming for.

It is interesting to note that most of these measurements were first defined by geographers in their attempt to measure landscapes: it is just a question of size. They were looking at meters, square meters ... and we are dealing with nanometers. I prefer to illustrate the problem with an example since it would take too long to explain each of these ratios. For a farmer, the size of a field is the multiplication of its length and width. For us, the measurement of the surface whose adhesion capability we are interested in qualifying is the total surface, meaning the sum of the surface of each clod of earth, and qualifying its lubrication capability could be done through the quantity of water that these ups and downs can contain to assert lubrication.

What do we have in our laser tool box?

A laser creates a powerful and narrow beam of light. When it collides with a surface, it is either reflected or transmitted, depending on the material and the wavelength of the light. All the examples here were made with infrared light (1064 nm) on steel, a material with a very high degree of absorption. Depending on the laser's power, a steel surface will be heated or will start melting or will be sublimated. This last case is what we know as ablation, where some steel particles will turn into gas, and the surface of the steel will be engraved.



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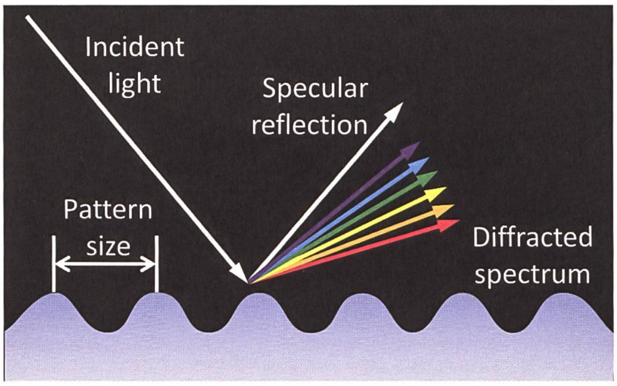

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The size of the spot depends on the focal length (the shorter the focal length, the smaller the spot) and on the wavelength of the light; a green light laser (532 nm) has a spot of 20 µm, whereas an infrared laser (1030 nm) has a size of 30 µm (the diameter of a human hair).

In our tool box, we have two different kinds of pulsed laser: either nanosecond (light pulse duration of some nanoseconds [10^{-9} sec]) or femtosecond (pulse lasting some femtoseconds [10^{-15} sec]). The main difference between them is that through femtosecond pulses the energy is so concentrated that 100 % of the material "touched" is sublimated – allowing high precision and creating a sharp aspect –, whereas in the case of nanosecond pulses, a non-negligible portion of the energy is dissipated into the material – melting the metal –, creating recasts, burrs and a smooth aspect.

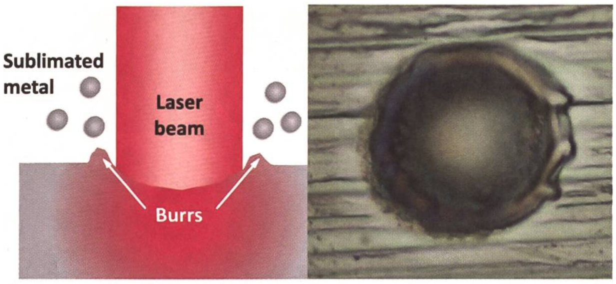
Coloring stainless steel

Stainless steel reacts to air spontaneously and forms thin native oxide layers; laser-enhanced material oxidation is based on thermal and non-thermal molecule surface excitations. Varying laser parameters such as power and scanning velocity will, therefore, influence the layer thickness, and this thickness will define how much white incident light is reflected from the sample.

Diffracting light

There are different ways of diffracting light; the most common one is the well-known prism. A number of structures can create structural colors by mechanisms such as a diffraction grating. A diffraction grating is a component with a periodic structure that splits and diffracts light into several beams travelling in different directions. The direction of these beams depends on the spacing of the grating "pattern size" and the wave length of the light so that the grating acts as the dispersive element.

Diffraction can create rainbow colors when illuminated by a wide spectrum light source (like the sun, for instance). This is the effect seen on the surface of CDs or DVDs due to the closely spaced narrow tracks on these optical storage disks. When the grating is made of parallel lines, the observer will sequentially see each of the rainbow colors by changing either his angle of vision or the angle of the incident light.



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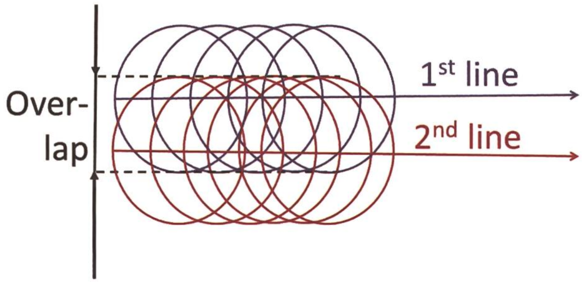

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Nanosecond pulsed laser machining

How do we create several micron-spaced lines with a tool, the laser beam, whose diameter is ten times bigger than the distance expected?

Once the focal length lens is selected and the laser wave length is chosen, the spot size is fixed. With our infrared laser and a focal length of 63 mm, both spot and crater sizes will be around 20 µm, which is still far too large. Of course, we can vary the power (meaning the depth of the crater) from 3 microns down to 0.1 micron, but neither this nor changing the frequency of "shooting" will give us the details we need to diffract the light.

Our only chance is to play with the little burr that is created at the edge of the crater when using a nanosecond laser. The "shooting" of the laser is usually done line by line, and we can obviously overlap the lines, so a small lip will be created between them. We tried to do this with a distance of 2 µm between the lines and it worked.

This solution involves many constraints, one being that we need to use a very short focal length, which reduces the capability to decorate 3-D surfaces due to some unavoidable collisions between the machine head and the part to be textured. Another one is the geometrical headache we get when we want to design parallel lines on a 3-D shape. There will always be some areas where we will need to stretch or shrink the distance between the lines.

Femtosecond pulsed laser machining

We recently launched a small and powerful machine, the LASER P 400, targeting watchmakers, jewelers and medical applications. This machine can be equipped with two different kinds of laser source that can be used alternatily. Half of our customers use this unique capability, employing nanosecond or femtosecond to achieve the textures or the structures they want. Let's see what "femto" can bring.

As already explained, a femtosecond lasts one million times less than a nanosecond, which means that the metal is instantly affected by a level of energy that is above the sublimation threshold. The result will be sharp and precise, no recast, no burr.

The wind of light

The sharpness is not the only specific aspect of femtosecond laser crater. At a nanoscopic level, the surface, after machining, shows ripples. This effect is usually called LIPSS (Laser Induced Periodic Surface Structures). The surface might show parallel lines (whose distance is related to light wavelength) or curved ones. According to specialists, line pattern is linked to light polarization.

Not only would it be too long to try to explain such effect, but I am unable to do it. I would rather say that this is the effect, the mark of "the wind of light", similar to the ripples created by the wind on the sand as shown in the picture of Coral Pink Sand Dunes State Park in Utah.

Ripples

Ripples are exactly what we need to diffract the light, and, in fact, we sometimes need to apply some finishing layers with a nanosecond laser (after "femto" engraving) in order to reduce this effect, as it is not always desirable. Of course, we are speaking here about iridescence, which means that the color will vary according to the vision angle. Realizing a color that is not influenced by light angle is still not feasible with our machines, but some universities are working on

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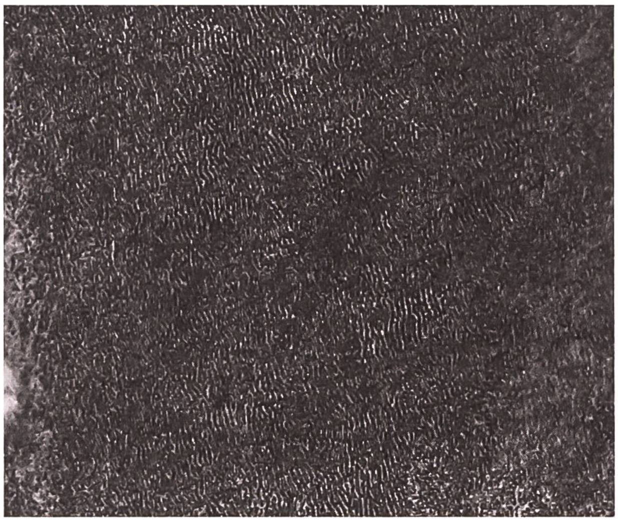

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7 Using a nanosecond laser, a little burr is created at the edge of the crater.

8 By overlapping two laser shootings a small lip is created between the lines.

9 The "LASER P 400" machine of GF Machining Solutions.

10 At a nanoscopic level, the surface that has been machined with a femtosecond laser shows ripples.

11 Ripples created by the wind on the sand in Coral Pink Sand Dunes State Park in Utah.

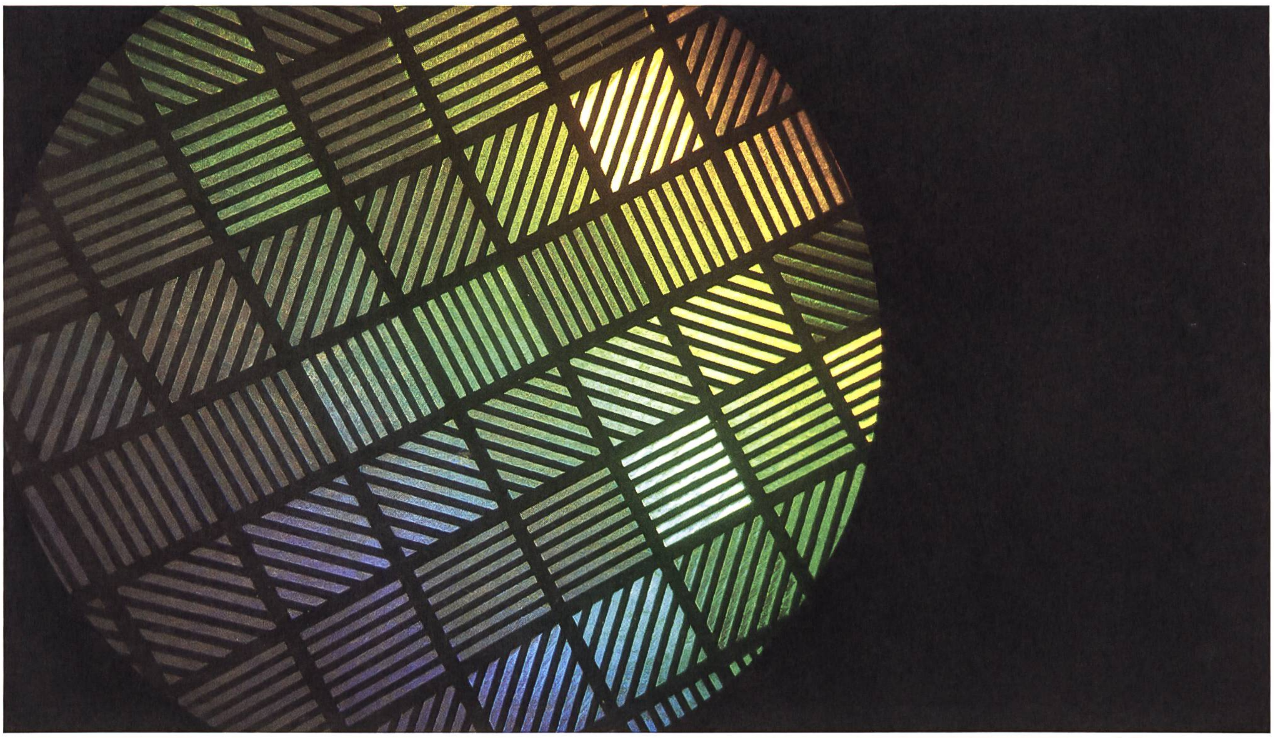
12 Diffraction of light (thanks to femto ripples) can create rainbow colors.

the problem and have been able, in lab conditions, to do it by combining several lasers on the same point. The effect is to create the required interference in order to display one color and to trap the others.

What is certain is that this effect has many potential uses. The distance between ripples varies with laser wave length: if the periodicity with infrared lasers is around eight hundred nanometers, it is smaller with green lasers and again smaller with ultraviolet lasers. The polarization of the light also plays a role, and some optical equipment is available to change it in linear, circular, azimuthal or radial fashion. This might still require some years, and no doubt lots of attempts that will not always be successful.

Spikes

If we increase energy, the ripples will gradually be transformed into spikes, very small and narrow pyramids. This effect has the characteristic of trapping light, appearing deep black to the human eye. This feature is being studied by optics companies in order to reduce parasite light on cameras as well as in automatic cars and for very sophisti-



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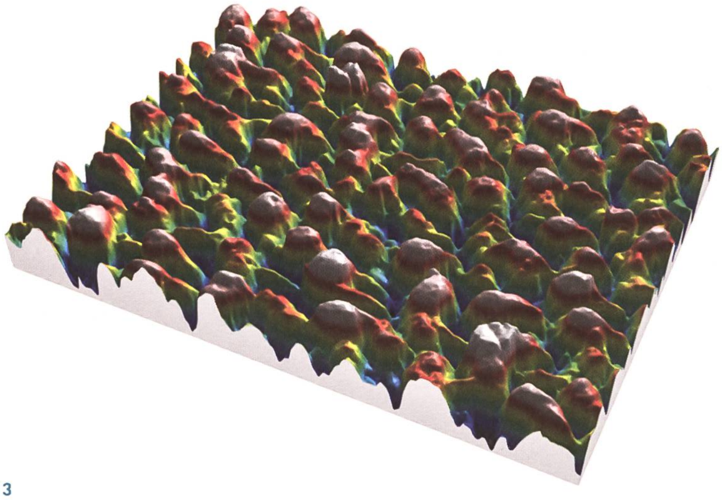

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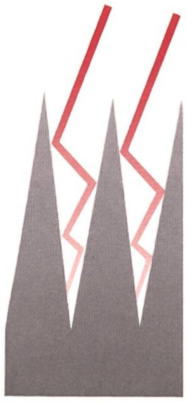


13 With increasing energy, the ripples are gradually transformed into spikes, very small and narrow pyramids.

14 The "wind of light" in Bryce Canyon in Utah.

15/16 Thanks to the Roctool™ injection process as well as selected plastic, nano-size details are not only present on the mold but also copied on the injected part, and its surface also diffracts the light in rainbow colors.

cated aerospace equipment. Any explanations would largely exceed my competencies, and, once again, I prefer to refer to the "wind of light", as shown on a picture of Bryce Canyon in Utah. Let's imagine the light blowing and shaping these nanometric summits. Where rocks were eroded during millions of years to create these wonderful shapes, we have here a similar aspect but created in femtoseconds. This comparison highlights an interesting link between duration and size, time and space.

What's next?

Creating nano-size functional surfaces on metal is and will remain quite complex and therefore expensive.

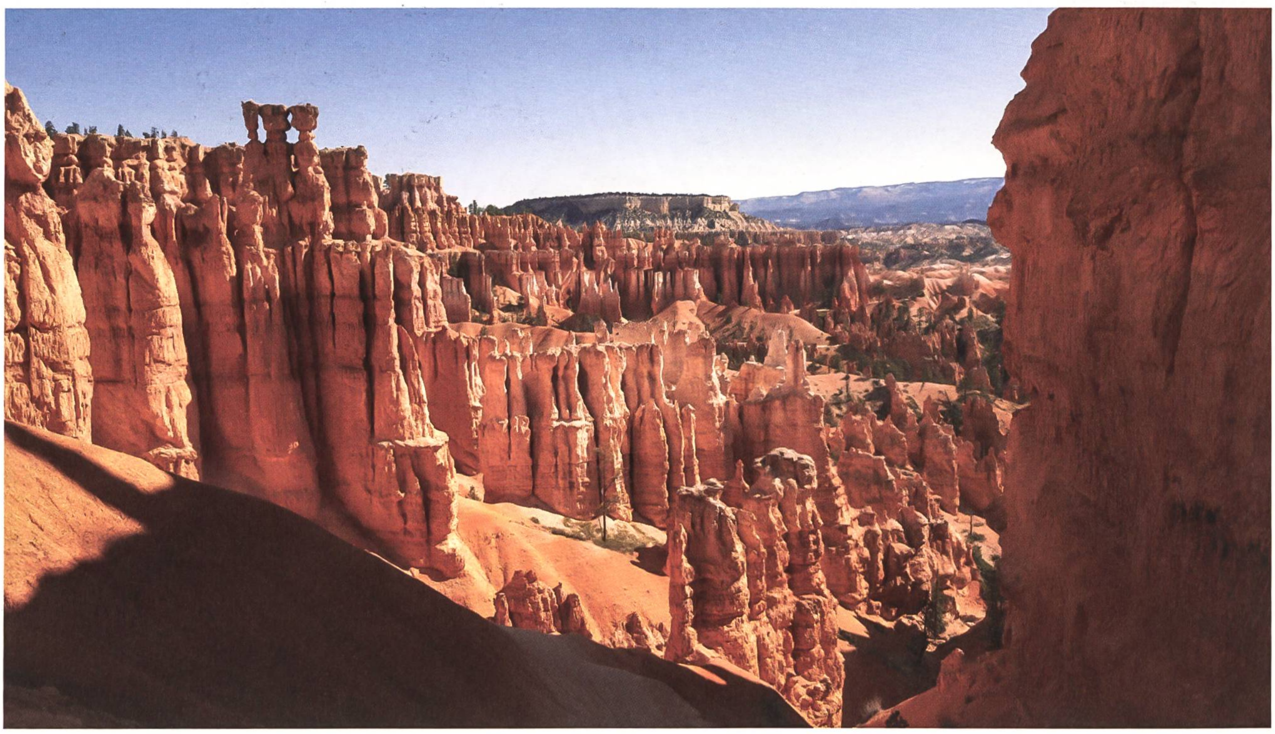
Our ultimate goal is to be able to make tools able to create parts with such properties. Here, the question is not only to structure the metal skin but also to work with plastic injection companies in order to make sure that the plastic injected part will have the same functionality. How nice would it be if furniture or windows were self-cleaning, elevator knobs anti-bacterial, critical airplane measuring sensors anti-icing?

Here, the breakthrough is at hand, and we could demonstrate it. Thanks to the Roctool™ injection process and selected plastic, nano-size details are present on the injected part, and its surface also diffracts the light in rainbow colors; we just created colors out of black.

Conclusion

We can't see the light through the air; we can only see the obstacles it collides with.

Our experience with light is a sequence of collisions. Our vision starts with the collision of the photons on our eyes' light sensors, rods and cones, and ends with the mind construct which we call reality, the encounter between



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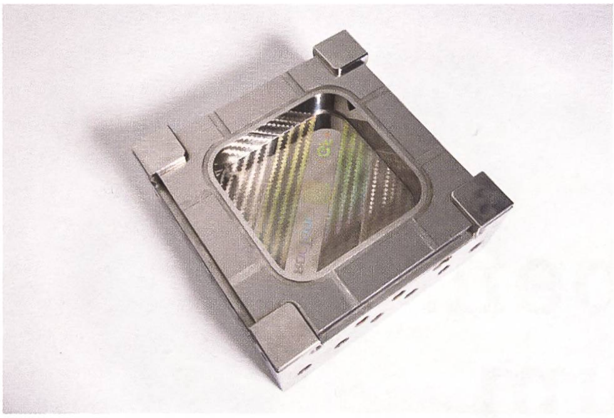

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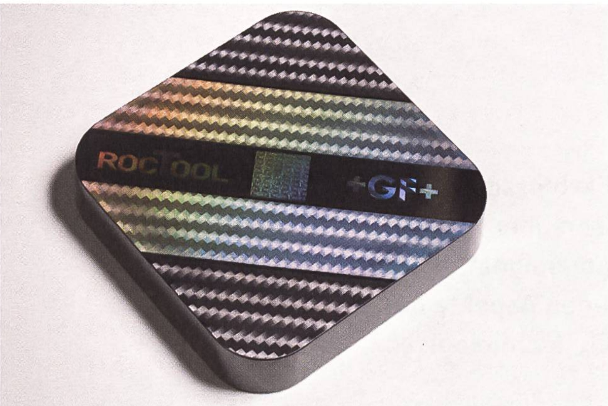

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our self-created image and our consciousness. There is no way to make sure that your neighbor sees the same colors on an iridescent plate, it all happens inside our mind, through the different senses we have. The lesson could be that we are the ones asked to color the world, to give it taste and smell, and what's better on a grey and rainy morning than a smiling face, hungry for what is to come and happy to share it. ■

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About the author

Jean-José Paccaud

After completing his software studies at the University of Geneva in 1984, Jean-José Paccaud decided to dedicate his career to the machine tool environment and joined Charmilles Technologies SA as a software developer for EDM machines. In 1991, he was promoted to manage the strategic collaboration between his company and FANUC, a famous Japanese company, to move from a 'home-made' CNC by leading FANUC products. Between 1995 and 2003, he held different leading positions in the EDM sector, first as Head of EDM wire standard products, then Head of EDM Die Sinking (DS) products, and lastly with a role in Automation (from electrode changer to robot cells), before becoming in 2003 Managing Director of Charmilles Technologies Maschinenbau AG in Schaffhausen. In 2006, he joined TORNOS (a well-known supplier of Swiss turning machines in Moutier) where he was in charge of developing products for the mid-range market, through Chinese and Japanese collaborations. In 2009, he decided to re-join the GF Group, holding the position of Managing Director of AgieCharmilles New Technologies SA. This company develops a complete range of laser machines that are primarily dedicated to texturing mold surface before offering functional surfacing such as hydrophilic, hydrophobic, oil retention or friction reduction.

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Picture credits

1–16 All pictures: GF Machining Solutions