2.1.2 Data storage within the surface of a component by cutting micro patterns

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2.1.2.1 Introduction of information into the component’s surface

Intrinsically incorporating component-specific information enables the communication of workpiece data without the use of additional aids, such as Kanban cards, printed QR codes, or bar codes. By storing product and process-related information together it is possible to identify a component throughout its life cycle.
The information is inserted by means of piezo-electrically actuated turning and milling tools which create micro patterns during the process of machining. Those micro patterns are able to encode data by means of basic binary encoding with the presence or absence of a structure representing a binary “1” or “0”, respectively. The method was developed for the turning process and subsequently transferred to the face-milling process. By the analysis of the cutting tool’s transmission behavior it was found that modulation and demodulation conditions apply, similar to data transmission by electromagnetic waves. The tool can be modeled as a linear time-invariant (LTI) system as long as it does not resonate.

Initially, binary nonreturn to zero (NRZ) base-band modulation was investigated as the simplest form of channel coding. After the identification of the transmission function (Fig. 2.1.2.1), it turned out that common requirements of distortion-free transmission were not satisfied. The first criterion is adequate signal-noise separation, which can be achieved by a minimum amplitude existing at 0 Hz. The second criterion, i.e., a constant signal group delay, was not satisfied, however. The group delay, which is equivalent to a linear phase response, was found to be nonconstant near 0 Hz in the base band because the actuator is controlled by an integration element. That means that the modulated signal must be free of direct components. The phase response is also nonlinear in the resonance range around 6 kHz where, however, the linear signal model cannot be applied. The next type of modulation chosen was a sine wave for the bit “1” and a constant zero progression for the “0” bit, which equates to binary digital amplitude modulation. The constant zero progression means reduced mean power and/or the mean amplitude can be doubled.

The generated signal sequence employing this type of modulation was cut into the component surface. For the rapid analysis of the signal and for the simulation of...
modulation and decoding, the actual actuator progression was recorded during the writing process (Fig. 2.1.2.1).

For encoding the data, standard methods of message transmission were examined together with the general parameters existing in this case, such as the signal delay due to the mass of the writing actuator. For channel coding, a turbo code was chosen, which is well suited for the kind of application, i.e., a low signal-to-noise ratio combined with high data volumes. The results were verified by simulations (Fig. 2.1.2.2). The bit error rates occurring in real conditions were determined by investigations using a channel model [1].

The encoded information needs be inserted directly into the workpiece in order to turn the workpiece into an information carrier. For this purpose, a new cutting tool was developed.

### 2.1.2.2 Piezo-electric actuator-driven turning tool

The piezo-electric actuator-driven turning tool was developed at the Institute of Production Engineering and Machine Tools. Referred to as a fast tool servo (FTS), the tool (Fig. 2.1.2.3) overlays the amplitude of a radially oscillating piezo-electric actuator with the cutting and feed rate in an external longitudinal turning process. Thus a pattern distribution can be specified by the variation of amplitude, amplitude progression, and frequency.

By driving the piezo-electric stack actuators braced by the base of the housing, the expansion of the solid-state actuator is transmitted directly to the motion of the indexable insert. The tool amplitude can be adjusted by connecting the actuators in series and in parallel.

![Dependency of signal-to-noise ratio of demodulated signal and bit error rate of decoded data.](image)
In order to be able to determine the deployment behavior of the structuring tool and to limit its range of use, a modal analysis is carried out. The determined first-order natural frequency of the tool is approximately 6500 Hz. The natural frequencies of the machine tool are identified in the range of 70 Hz and 7000 Hz, indicating that no superimposition of the various natural frequencies is to be expected. In order to avoid nonlinear effects arising from the natural frequencies, all investigations for the determination of suitable process parameters for the FTS to cut micro patterns are carried out in the range of 2000–5500 Hz. When the tool cutting edge is in contact with the workpiece, the amplitude progression shows virtually constant attenuation without a shift in the natural frequency. As a result, a constant reduction of the tool tip deflection at different frequencies in the working range and with varying amplification factors can be assumed [2,3].

Once the working range of the actuated turning tool has been determined, it can be used to introduce surface micro patterns. Fig. 2.1.2.4 shows micro patterns within a surface. In order to achieve clearer track depths and widths, the signal is substantially amplified so that on real components the pattern depths are within the range of 4–6 μm. Before storing the information, the alphanumeric sequence “SFB_653” is converted into a signal sequence using the modulation methods described earlier. The information can be read out in cutting direction. Thus a track profile contains the signals for the digit “1”, observable as dark areas, and for “0”, observable as light areas. The signals have a defined separation from each other, which results from the proper combination of excitation frequency $f_e$ and cutting speed $v_c$. The data density along a track cannot be infinitely increased as the natural frequency of the tool must not be exceeded and the cutting speed should not be less than $v_c = 200$ m/min for the technological reasons set out earlier. The feed rate $f$ also affects the data density, at least in component axis direction. For technological reasons, the data density cannot be infinitely reduced either. Therefore the maximum data density is restricted to...
Another process variable is the amplification factor $K$, which affects the depth of the micro patterns [4].

### 2.1.2.3 Piezo-electric actuator-driven milling tool

Another main focus of the research is the development of a spindle system to produce micro patterns on flat surfaces and the description of the interrelationships between the manipulated and system variables of the new process and the produced surface. Based on the knowledge gained from the development of the activated turning tool, a piezo-electrically actuated tool for the production of micro patterns in a milling process is developed. Fig. 2.1.2.5 shows the design of the milling tool [5,6].

To produce axial deflection of the milling cutter tip, a ring actuator with a maximum force of $F_{\text{max}} = 20$ kN and a deflection of $a_{\text{max}} = 60$ μm at a maximum permissible voltage of $A_{\text{max}} = 1.0$ V was used. The system is mounted by two diaphragms made of spring steel acting as solid-state joints. The use of a ring actuator increases the performance capacity compared with cylinder actuators due to the larger surface area and the associated better thermal properties. Furthermore, the ring design allows rotationally symmetrical, central spring loading by disc springs. For use in machine tools, the milling tool has a standard HSK-A 63 shank. Due to the high power to be transmitted, a slip ring is employed. In addition to the voltage, this slip ring also
transmits a temperature signal and a strain gauge signal to determine the expansion of the actuator. The use of titanium for the tool body reduces the rotating mass including a conventional screw-in milling head ($D = 20\,\text{mm}$) to 320 g. This enables a highly dynamic controlled excitation (natural frequency $\omega_0 = 4.7\,\text{kHz}$). A precise real-time control system based on a static and dynamic characterization of the system is constructed. By coupling the FTS control to the machine tool control, the patterns can be produced according to the main spindle’s rotational angle [7,8]. Both the actuated tool and the technology described later are the subject of patent applications and have already been put into practical use in industrial applications [9].

Thus the classic flat milling process is supplemented by the two controlled variables, structuring frequency $f_s$ and structuring amplitude $a_s$. The main variables influencing surface and micro pattern quality were determined on the basis of a static testing plan. An approach for measuring surface roughness along the tooth cutting arc is developed in order to determine the micro pattern quality and the effect of axial excitation on topography. A confocal microscope with suitable algorithms for profile distortion correction is applied. The surface roughness along the tooth path decreases with increasing cutting speed and structuring frequency. An increasing rake or clearance angle has a comparable effect. In feed direction, the influence of the structuring amplitude on the roughness is 2.5 times higher than the influence of the structuring frequency. Feed per tooth and clearance angle are significant influencing factors in this context. The results correlate with the existing findings without axial excitation [10,11].

The resulting data density is restricted by the kinematic relations. The number of patterns along the tool’s engagement is determined by the relation between the
structuring frequency $f_s$ and the rotational speed $n$. The number of patterns in feed direction is determined by the structuring amplitude $a_s$ and the feed per tooth $f_z$. In order to generate patterns with defined depth and length, an exact control of the axial tool movement is essential [12–14].

In order to demonstrate the process kinematics and the achievable quality of the patterns, comparative tests are carried out on Al7075, C45, 42CrMo4, and TiAl6V4. For this purpose, the actuator is stimulated with a sinus oscillation every 15 rotations during finish milling in order to generate defined patterns in the surface. To change the pattern’s length and depth, frequency and amplitude are varied on two levels. Cutting speed and feed rate are set according to a finish milling depending on the particular material. The process parameters are summarized in Table 2.1.2.1.

Furthermore, two cutting edges are used that differ in their width between 250 and 500 μm. Fig. 2.1.2.6 shows the cutting edge’s geometry.

### Table 2.1.2.1 Process parameters depending on the workpiece material

<table>
<thead>
<tr>
<th>Material</th>
<th>Rotational speed [min$^{-1}$]</th>
<th>Feed per tooth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al7075</td>
<td>3500</td>
<td>0.08</td>
</tr>
<tr>
<td>C45</td>
<td>3000</td>
<td>0.06</td>
</tr>
<tr>
<td>42CrMo4</td>
<td>3000</td>
<td>0.06</td>
</tr>
<tr>
<td>TiAl6V5</td>
<td>2500</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Fig. 2.1.2.6 Cutting tool for binary structuring.
By using these cutting tools it is possible to generate defined patterns in the work-piece surface during the finishing process. As an example, generated patterns in TiAl6V4 are shown in Fig. 2.1.2.7. The figure is made with a confocal white-light microscope.

The characteristics of the generated micro patterns vary for the four different materials. These variations occur in form of geometry and the distance between the patterns. Furthermore, the surface roughness varies depending on the workpiece material and the corresponding process parameters.

2.1.2.4 **Structure geometry depending on the workpiece material**

The depth of the micro patterns is affected by the engagement depth of the tool, which results from the oscillation amplitude $a_s$, specified by the given electrical voltage $U_{cp}$. For the experimental evaluation, the tool’s oscillation amplitude is varied on two levels at 10 and 20 $\mu$m. However, these are the oscillation amplitudes that appear on idle mode without engagement in the workpiece surface. Although the pattern depth can be increased by increasing the oscillation amplitude, the measured pattern depths are lower than the given ones. The given amplitude $a_s = 10 \mu$m can be reached more easily than the amplitude of 20 $\mu$m. Fig. 2.1.2.8 depicts the depth of the micro patterns depending on material, amplitude, and frequency for cutting edge width of 250 $\mu$m. A cutting edge width of 500 $\mu$m shows comparable tendencies. The pattern depth does not depend on the workpiece material. Machining of Al7075, which is the softest of all four materials, generates the deepest structures. Furthermore, pattern depth does not show a dependency on oscillation frequency either. As shown in Fig. 2.1.2.8 in the lower diagram, a change of the frequency from 1000 to 1500 Hz decreases
the pattern depth for a given oscillation amplitude of 20 μm. For an amplitude of 10 μm this cannot be confirmed. As the amplitudes during engagement differ from the idle amplitudes, further investigations have to be conducted concerning the engagement conditions of the cutting edge in the workpiece’s subsurface.

The geometry of the generated micro patterns is examined with respect to their length and width. Fig. 2.1.2.9 shows the length depending on the oscillation amplitude for both frequencies, 1000 and 1500 Hz. According to the results, the variation of the oscillation amplitude between 10 and 20 μm shows no significant influence on the pattern length. An increase of the frequency from 1000 to 1500 Hz leads to a reduction of pattern length. For all workpiece materials, a higher frequency leads to a decrease of the pattern length. Machining of TiAl6V4 generates the shortest patterns. This can be explained with the fact that this material shows the highest resistance to machining due to its material properties. The main reason can be found in the low Young’s modulus of 110 GPa and the high yield strength of the used alloy TiAl6V4. This leads to a high amount of springback and mechanical deformation resistance during tool engagement [15].

Besides the pattern geometry, the density of the generated patterns can be investigated. For this, the four workpiece materials are machined. During machining, the oscillation frequencies of 1000 and 1500 Hz are compared. In order to link the
investigation to the practical application, the machining tests are conducted with the material-depending finishing parameters. The finishing parameters and the obtained results are summarized in Table 2.1.2.2. Thus it can be deduced which density of binary information can be reached for each material with the recommended finishing parameters. TiAl6V4 shows the highest density of patterns because the lowest rotational speed $n$ and lowest feed per tooth $f_z$ are recommended for finishing.

<table>
<thead>
<tr>
<th>Material</th>
<th>Rotational speed [min$^{-1}$]</th>
<th>Feed per tooth [mm]</th>
<th>Number of patterns/$f_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al7075</td>
<td>3500</td>
<td>0.08</td>
<td>10 14</td>
</tr>
<tr>
<td>C45</td>
<td>3000</td>
<td>0.06</td>
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</tr>
<tr>
<td>42CrMo4</td>
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<td>0.06</td>
<td>8 14</td>
</tr>
<tr>
<td>TiAl6V5</td>
<td>2500</td>
<td>0.04</td>
<td>42 60</td>
</tr>
</tbody>
</table>

Fig. 2.1.2.9 Length of micro patterns depending on material, amplitude, and frequency.
Next, the roughness after machining different workpiece materials is shown. Using the finishing parameters depending on the workpiece material, the roughness in the area without micro patterns differs. The highest roughness value can be found after machining C45 as shown in Fig. 2.1.2.10. The other three machined materials show no significant difference in their surface roughness.

The surface roughness depending on the tool’s cutting edge width is shown in Fig. 2.1.2.11. It can be seen that for all materials and for both operation frequencies a higher surface roughness results from the use of the tool with a cutting edge width of 250 μm. The reason for this can be found in the fact that the wider cutting edge takes away material from the prior cutting path and thus smooths the previously cut area. This leads to a lower surface roughness.

### 2.1.2.5 Process forces during cutting of micro patterns

Besides the generated geometries, the forces during the cutting process are examined with analogy experiments. They consist of single toothed face milling with an excited sinusoidal oscillation. Forces of the binary structuring process machining Al7075, C45, 42CrMo4, and TiAl6V6 are determined. In analogy to the binary patterns, the generated patterns are locally isolated and do not overlap.

The process parameters cutting speed, feed rate, cutting depth, oscillation frequency, and oscillation amplitude are varied in two steps. The force measurement
is adjusted by the self-oscillation rate of the force measurement plate based on the response characteristics. The structuring forces are clearly separable from the milling forces and identifiable as additional loads in cutting and passive directions (Fig. 2.1.2.12). The characteristics of the additional force components $F_s$ are only influenced significantly by the structuring amplitude $a_s$ and neither by the structuring frequency $f_s$ nor by other process parameters. The structuring forces can be considered separately and expressed by a linear behavior of a defined incremental factor (Eq. 2.1.2.1) depending on the structuring amplitude. This factor depends on the material and the process conditions, e.g., specific cutting force. Additional tests with further amplitudes do not disprove the linear characteristic. This described behavior is proven for all investigated materials. Differences only exist in the magnitude of the structuring forces. The process forces in cutting and passive direction can be added up to the amount of the forces out of conventional face milling and structuring (Eq. 2.1.2.1) [16,17].

$$F_{i,\text{total}} = F_{i,\text{regular}} + k_{i,\text{struc}} \cdot a_s(S(\varphi)) \quad \text{with} \quad i = c,z$$

(2.1.2.1)

$F_{i,\text{regular}}$ represents the cutting forces without structuring. The constant $k_{i,\text{struc}}$ is the gradient coefficient, which is calculated as a product of the specific cutting force

Fig. 2.1.2.11 Surface roughness in the finished surface without micro patterns depending on the tool width.
constant and the equivalent chip thickness. The structuring depth depends on the deflection signal $S(\varphi)$, which in turn depends on the engagement angle $\varphi$.

It has been demonstrated which surface topographies result from cutting of micro patterns depending on process parameters and workpiece material. In the following, the process of reading the generated micro patterns is investigated.

### 2.1.2.6 Reading information-carrying micro patterns

The reading algorithm for turned micro patterns [1] proved suitable to be adapted to micro patterns produced by flat face milling. To that end, the existing read out process was expanded by automatic distortion correction. That involves nonparametric arc curvature estimation utilizing the periodic structure of the image [8]. The main wavelength of the image intensity values in feed direction, which is robustly determined using the ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques) [18] spectral estimation method, represents the track separation. The track deviation from an assumed array of parallel tracks is equivalent to the local phase offset of the signal. The latter is determined based on the estimated frequencies. However, the phase still has to be unwrapped due to its $2\pi$ ambiguity. Subsequently, the image undergoes geometrical distortion correction and rectification such that tracks are sufficiently parallel (Fig. 2.1.2.13).
The technology described in the preceding sections for the storage of information on workpiece surfaces using micro patterns was investigated with regard to data security in the case of near-realistic surface damage. The initial bases for the investigation were car drive shafts and CV joints after 10, 15, and 20 years of use on the vehicle. Damage characterization reveals a dominance of surface change due to corrosion. Mechanical damage occurred to a minor degree, while no thermal damage was found.

For a controlled damage simulation, information-carrying specimens were corroded in salt-mist spray chambers. As corrosion increases, the mean uncorrected error rate (proportion of incorrectly detected bits relative to total number of bits before any error correction) increases from $2 \times 10^{-3}$ to $9 \times 10^{-2}$ after 6 h and $2 \times 10^{-1}$ after 9 h due to local concentrations of heavy corrosion. Beyond 15 h, data reading ceases to be possible because the algorithm for track synchronization fails. In addition, investigations were carried out concerning mechanical surface damage. Therefore scratches were incrementally introduced to the surface on a lathe. In these cases, the bit error rate increases to $9 \times 10^{-3}$. Those two errors, which simultaneously affect multiple bits of a symbol, correspond to a two-dimensional burst error in communication technology terms. To increase the robustness of the process and the security of the data against surface changes, the results were used as the basis for designing forward error correction (FEC) according to the expected surface damage (Fig. 2.1.2.14). For that purpose, a Reed-Solomon (RS) block code was used. The resistance to burst errors was increased by the development of a block-interleaving scheme that swaps the bits of a data block according to a pseudorandom permutation pattern after encoding and before application to the surface. Due to the use of RS FEC and the interleaver, it was possible to achieve quasi-errorless reading of the data with scratched and corroded specimens. At the same time, an information density of 2 kbit/cm$^2$ was achieved.
The effect of subsequent coating on data readability was determined. The PVD coating process shows no negative and sometimes even a positive effect on the detection of structures, regardless of coloring. That also applies to different layer types and thicknesses. The property of the process to amplify the roughness peaks of the topography has a positive effect on data readability. The reading system only had to be slightly adjusted to the different reading conditions [19] as the existing image processing methods already demonstrate adequate immunity to topography changes. Smoothing coating processes such as CVD, chemical wet deposition coating, or the application of paints had a negative effect due to the reduction of pattern depth and resulted in increasing data loss even at small layer thicknesses.

To improve data reconstruction and signal quality, two methods of sensor data fusion were evaluated. The use of RGB color cameras instead of monochrome cameras did not show any advantages over the existing process. Nor was any improvement in data reconstruction achieved by the analysis of stereoscopic images created by a pair of cameras because the substantial reflections from metallic surfaces did not allow a sufficiently accurate registration of both stereo images. Significant improvements were achieved, however, by the fully automatic reading of information-bearing micro patterns. For that purpose, a large number of optical, geometrical, machining technology, and signal parameters are estimated. Data reading algorithms use experimentally optimized parameter sets as a priori knowledge. Thus the number of degrees of freedom, i.e., the scanned area can be reduced, which means an improvement of computing efficiency. In that way, improvements of two orders of magnitude were achieved so that the execution time is now around 0.5–1.5 s depending on the applied parameters.

Besides the workpiece’s surface, the tool properties have an influence on the quality of generated micro patterns. So, tool wear has been investigated additionally. Due to the fluctuating machining cross-section and fluctuating contact
length, excitation has a negative effect on wear. In particular, the flank wear on the end-cutting tip increases with rising amplitude (Fig. 2.1.2.15).

As shown, the quality of generated micro patterns is important for the readability. Thus it can be of advantage to predict the micro patterns’ quality before the machining process is performed. One method is a simulation model which may help to predict the generated micro patterns. This will be shown in the following section.

2.1.2.8 Process design for generating and simulating binary structures

In order to generate a method for the process design, a surface simulation applying a dixel-based surface simulation software CutS is constructed. It allows the generated surface to be mapped based on kinematic connections (Fig. 2.1.2.16).

Furthermore, the theoretical roughness depending on the cutting edge geometry and based on the process parameters can be determined. The area requirements for a defined binary pattern can also be determined simulatively. The simulation model is suitable for mapping the generated surface after cutting of micro patterns binary patterns into a workpiece surface. However, there are differences between the simulated and the actually measured surface roughness. As an example, this is shown for the roughness value $S_a$ in Fig. 2.1.2.17.

In order to improve the model’s results, this simulation model should be expanded to consider the tool’s behavior shown in this paper. Also, the influence of different workpiece materials on the binary pattern geometry could be integrated into the simulation to generate results that are closer to the measured surfaces after the machining process.
2.1.2.9 Possibilities and limitations of the structuring process

To demonstrate the potential of the kinetics of actuated face milling with one cutting edge for specific surface topography manipulation a tool prototype with a slip ring for energy transmission is used. Due to the slip ring energy transmission, this prototype is...
not suitable for converting a trigger signal into a movement of the piezo actuator. The main reason for this can be found in the physical fact that the inductive energy transmission cannot transfer DC voltages but only changes in the voltage. Therefore a constant deflection of the piezo actuator is not possible. However, after the extension and adjustment of the tool control the generation of any patterns and structures in one milling path is feasible, as shown in Fig. 2.1.2.18 [14].

First, based on any chosen gray scale image, a structuring matrix is generated as a preparation step. This matrix contains the tool’s deflection signals depending on the position in feed direction and the momentary rotation angle of the cutting edge. The size of the matrix is predefined by the maximum amount of deflections per rotation (structuring frequency), the cutting speed, and the feed velocity. Next, together with the information of the spindle’s rotation position, the matrix is processed by a Matlab/Simulink model. It is necessary to handle the signals in real time. For this reason, a dSPACE real-time computer system is used for the model. Its sampling rate is $f = 40 \text{ kHz}$ to discretize the maximum structuring frequency of $f_s = 4 \text{ kHz}$ into 10 graduations. This is necessary to guarantee an approximately homogeneous movement of the tool tip. A position control is not realized in this control solution. The system’s trigger signal is amplified by a high-voltage amplifier and transmitted to the piezo actuator. The control principle of the tool system is given in Fig. 2.1.2.19.

Furthermore, this control principle allows the generation of several large-scale textures or patterns of various milling paths next to each other, as to be seen in Fig. 2.1.2.20. With the help of a trigger signal, which is activated by the rotary encoder of the feed drives, it is possible to start each pattern at the same position so that the
generated patterns are equally positioned. This way two patterns may be generated on two adjacent milling paths without an offset between them. So far, a small material web remains between the milling paths. However, this is an issue that can be solved in the course of further optimizations. By using this control principle, it becomes possible to mill textures and patterns with medium feed velocity within a short amount of time (about 5 s/cm²).

The conducted tests show that an actuated fast tool servo is capable of generating defined micro patterns. Furthermore, the subsurface is affected by the axial tool excitation in terms of residual stresses. This opens the opportunity to define not only the workpiece’s topography but also the residual stresses. The investigations of inducing residual stress by actuated cutting and hammer peeling are described in Chapter 3.3.
2.1.2.10 Summary

It was successfully demonstrated how data can be introduced directly into a work-piece surface by means of piezo-electrically actuated turning and milling processes in machining. For that purpose, the internally developed tool concepts were characterized according to their behavior in use and suitable operating conditions were derived. By the use of the binary number system, it was possible to encode information on the component surface and read it back using an optical process. The use of the actively affected deterministic surface component now makes it possible to record process and product-related information directly on the component. Thus it is conceivable that, in the future, products will be able to self-authenticate and independently control their own path through the production and/or maintenance processes. The application of the process to different materials was investigated and a simulation approach described to predict surface topography after the actuated machining process. The used methods were tested for robustness by means of corrosion tests and mechanical damage.

References

2.2 Employment of subsurface properties

In this chapter it will be demonstrated how a component’s subsurface can be used as an information source for experienced loads, furthermore different possibilities of using a component’s subsurface as a data storage unit will be presented.

Imagine mass produced components had sensory properties. Which opportunities would arise if millions of wheel carriers or passenger car drive shafts could give detailed information on mechanical loads during their life cycle? Which impact would safety-relevant components such as engine mounts have if they reported on the maximum load stress they have experienced since the last inspection? Rather than attaching sensors to a component, its subsurface properties can be used to provide information on loads during its life cycle. Future mass production components that give feedback during their application represent an invaluable benefit for maintenance planning as well as for design evolution regarding tailored adaptation to load.