Resistant in Every Position

Polyetherimide is one of the materials suitable for additive manufacturing procedures. Strength investigations of samples specially made of this high-performance plastic provide information about the long-term behavior of end products under different storage conditions and durations as well as environmental influences.

Test specimens for determining strength and resistance (figures: KTP)

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Fused Deposition Modeling (FDM) is an additive manufacturing procedure, with which thermoplastic components are built up directly in layers from 3D-CAD data **(Fig. 1)**. Since 2003, this process is one of the most widely used additive manufacturing procedures [1] for creating prototypes, molds, and end products. Sabic Innovative Plastics in Bergen op Zoom/The Netherlands supplies polyetherimide (PEI), which can be used for this technology, and thanks to its properties it is also particularly interesting for the aerospace and automotive industries [2, 3].

The Direct Manufacturing Research Center (DMRC) of the University of Paderborn, Germany, has focused on integrating the additive manufacturing process as a mass-production method. The subject matter covers application-related research and basic research. First mechanical investigations have been conducted at the DMRC, in order to determine the mechanical strength values of samples produced with FDM using PEI as material, and in dependence of build orientation and internal structure [4 to 6]. Depending on build orientation and structural parameters, the strength values are comparable with the properties of injection molded components [7 to 8]. Consequently, this technology has great potential for direct application of the manufactured components. In order to draw conclusions about the time-dependent change of strength values depending e.g. on temperature and ambient conditions, further experimental in-

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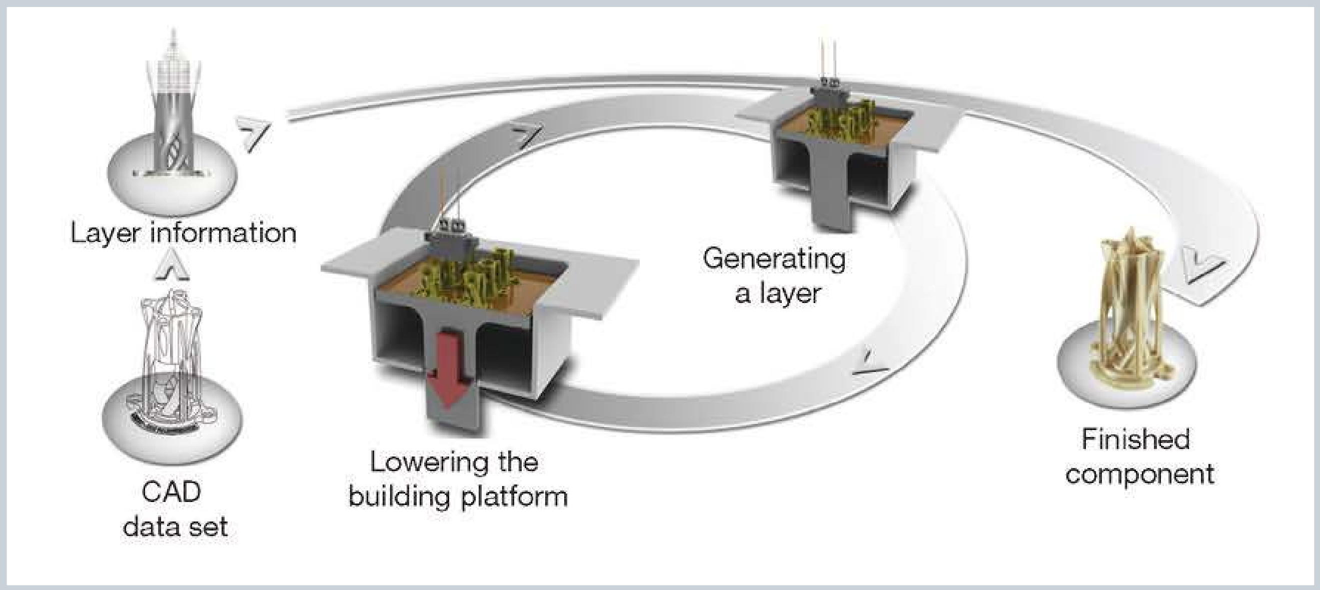

Fig. 1. Schematic diagram of additive manufacturing using the FDM procedure

vestigations were carried out at the DMRC in Paderborn. For this purpose, test specimens were stored for different lengths of time, and subsequently subjected to a tensile test at different temperatures. Likewise, samples were subjected to artificial and outdoor weathering, in order to investigate the environmental influences on the measured strength values. Additionally, test specimens were subjected to changing climatic conditions.

Tensile tests in accordance with the American Standard ASTM D638 were carried out on a Fortus 400mc system of Stratasys Inc., Eden Prairie, MN/USA, using the standard parameter settings for the Insight Software Version 7.0. in two different orientations **(Fig. 2)**. Due to the process, laterally built-up samples exhibit good strength values, whilst vertically built-up samples exhibit lower values.

Tensile Strength

To analyze the long-term strength properties, the manufactured test specimens were stored for different lengths of time ranging from one week up to 52 weeks in two different ambient conditions: at room temperature (23 °C and 50 % relative humidity) and at room temperature completely submerged in water **(Title figure)**. Subsequently, a strength analysis was conducted on the test specimens at different temperatures between -60 °C and +160 °C. The resulting strength values of the test specimens are determined from the tensile strengths. Every data point represents the mean value of 10 test specimens in total of a build job.

Figure 3 shows the tensile strengths of the laterally and vertically built-up samples that had been stored for different durations of 1 to 52 weeks, and were tested at room temperature. The strengths remain constant for all storage durations, and also the water-stored samples showed no changes. Compared with laterally built-up samples, the tensile strengths of vertically built-up samples are lower, because the layers are fused due to heat conduction. Consequently, the tensile strength represents the binding quality between individual layers. The slight strength variations of vertically built-up samples, and the higher standard deviations can be explained by the fact that vertically built-up samples are more sensitive to process variations. But all the values lie within the standard deviation. This also means that the manufacturing process is robust and reproducible. Prerequisites for this good reproducibility are regular checks of all relevant system components, regular machine maintenance, and regular replacement of all wear parts.

The tensile strengths of the samples tested at other temperatures also exhibit constant values. **Figure 4** shows the averaged tensile strengths of the two build orientations for all storage durations at the respective test temperatures. The highest strength values are achieved at the lowest temperatures, and become lower with increasing temperature. For both build orientations, the wet-stored samples achieve the same temperature-dependent tensile strengths. Consequently, storage conditions do not influence the mechanical strength values.

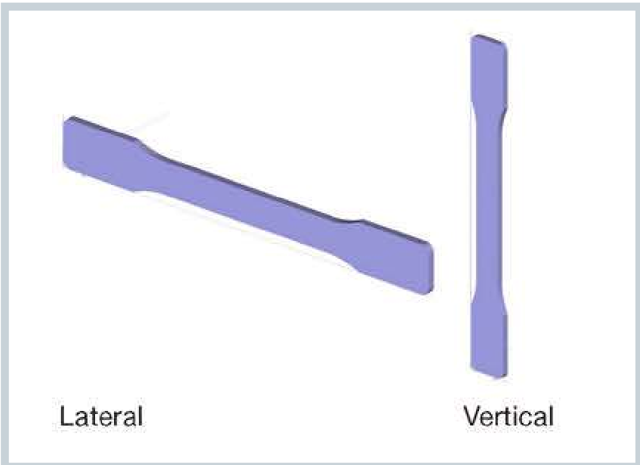

Fig. 2. Different build orientations of tensile tests

Resistance

In addition, artificial and outdoor weathering tests were conducted on FDM samples made of PEI, in order to investigate →

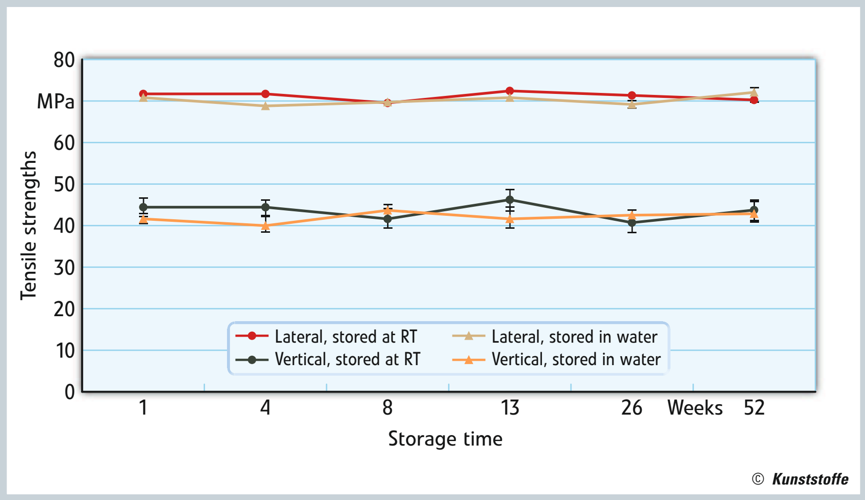

Fig. 3. Determination of long-term strength at different test temperatures of FDM samples made of PEI

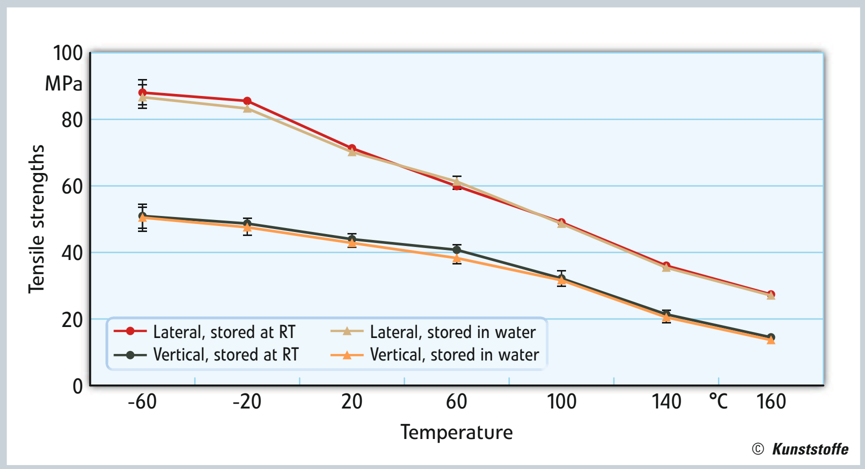

Fig. 4. Determination of temperature-dependent strength values of FDM samples made of PEI

resistance against environmental influences. Also for these tests, the standard parameter settings of the Insight Software Version 7.0 were used on samples with both build orientations (lateral and vertical).

During artificial weathering, the test specimens were subjected to a wavelength of 300...400 nm for a duration of 100...500 hours in a suitable weathering unit. The resulting tensile strengths with the respective standard deviations for the two build orientations are shown in **Figure 5** for different weathering periods, and are compared with the averaged strengths from the previous long-term analysis, shown as 0 h storage time.

The tensile strengths of the laterally built-up samples remain constant for all weathering periods. Contrary to this, and after artificial weathering of 100 hours, vertically built-up samples exhibit slightly lower tensile strengths, but which then remain constant with longer exposure times. Moreover, all tensile strengths lie within the existing standard deviation. In summary, the strength values exhibit no changes as a result of exposure to artificial weathering for a period of up to 500 hours. However, slightly lower values for elongation at break were determined with both build orientations, which suggests an embrittlement of the material. In addition, a color change of the material was found on all samples after weathering. This indicates a lack of UV resistance.

Outdoor weathering was carried out on the roof of a Paderborn University building. Hereby, the samples were mounted on a suitable weathering frame. Weathering took place from March 2012 to March 2013, whereby samples were subjected to mechanical tests after 1, 4, 8, 13, 26, and 52 weeks respectively. Moreover, reference samples from every build order were stored in a closed box at an ambient temperature of 23 °C and a relative humidity of 50 %.

Figure 6 shows the resulting tensile strengths as a function of weathering period with the respective standard deviations, and compared with the averaged strengths from the long-term analysis, shown as 0 week storage time. For the first eight weeks of natural weathering, the tensile strengths of laterally built-up samples exhibit the same values. Reduced strength values are measured after 13 weeks, and a significant reduction is found after 26 weeks. In comparison with the averaged strengths of the long-term analysis, the weather resistance properties of vertically built-up samples exhibit reduced strengths already after one week, but the reference samples have the same values. Therefore, no change of the strength values of the vertical samples is apparent during the entire weathering time of 52 weeks.

Consequently, outdoor weathering has a negative effect on laterally built-up FDM components after 26 weeks, which were tested after the summer months. This indicates that the material used does not have adequate UV resistance, and is

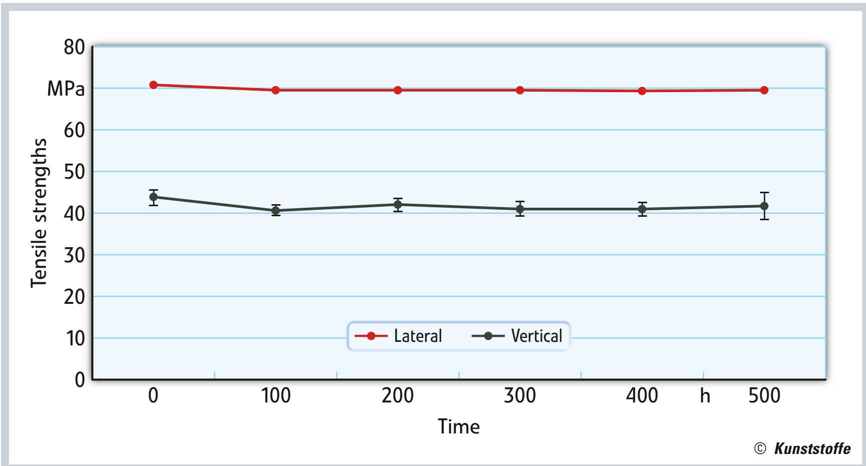

Fig. 5. Determination of strength values of FDM samples made of PEI after different periods of artificial weathering

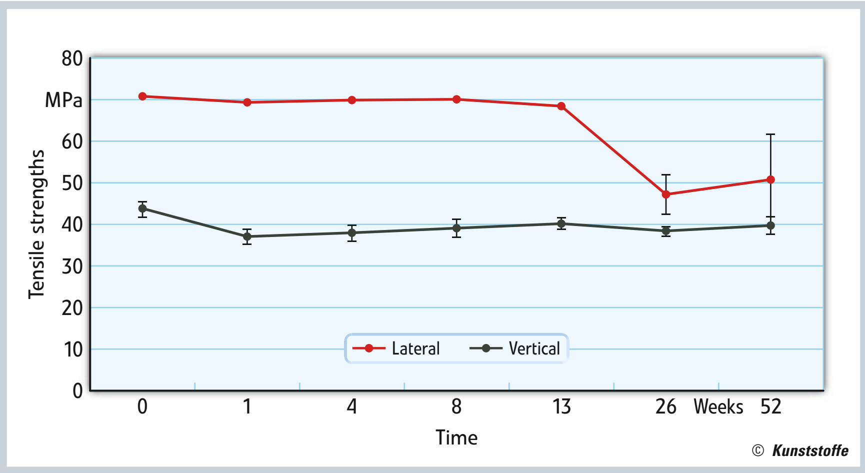

Fig. 6. Determination of strength values of FDM samples made of PEI after different periods of natural weathering

damaged by outdoor weathering, which in turn has a negative influence on the strength values. Vertically built-up samples, on the other hand, exhibit no changes in tensile strength. Therefore, the binding quality between the layers is not affected. Also here, a clear change in material color was detected after the natural weathering period.

In order to investigate the thermal resistance in more detail, test specimens were also subjected to changing climatic conditions. For this, a temperature range between -60 °C and +175 °C was selected, and the cycle time was six hours without regulation of humidity. The test specimens were exposed to this temperature cycle for up to four weeks. Hereby, the tensile strengths show hardly any change even after four weeks [6]. This means that FDM samples made of PEI have a good resistance to changing temperatures.

Summary

The investigations showed that FDM samples made of PEI material exhibit temperature-dependent strength values. However, these do not change under different ambient conditions and with longer storage durations. Moreover, the FDM procedure is a robust and reproducible manufacturing process. Also after thermal cycling, no changes in resistance were observed. Artificial and outdoor weathering showed that with FDM samples made of PEI, the reduction in strength is material-dependent – presumably due to inadequate UV resistance. Process-dependent changes in strength could not be determined. Consequently, this technology has great potential for direct application of the manufactured components, also regarding the long-term strength under different ambient conditions. ■

REFERENCES

The comprehensive references are listed at www.kunststoffe-international.com/A065

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