Optimization Strategies for Micro Parts

Micro Injection Molding. In comparison to macro parts the in-service properties of technical micro parts are negatively affected by the flow and cooling conditions experienced during injection molding. Low thermal conductive mold materials, however, show a large potential for improvements.

ARIANE JUNGMEIER
DIETMAR DRUMMER
GOTTFRIED W. EHRENSTEIN

In many technical areas the miniaturization of components plays an increasingly important role. This can be seen in the continuous growth of the market for micro systems technology in the past few years and the ongoing growth rate of about 10 % predicted up to 2020 [1]. In this exemplary market micro parts are becoming an ever more significant factor. Current applications are found in particular in the areas of biotechnology, optical systems, machine components, medical technology, micro fluidics and micro electronics.

The small dimensions of micro parts place special requirements on the processing technology in particular in respect of the flow and cooling conditions. Various developments in machinery subsystems as well as mold and process technology have already been realized and successfully implemented at an industrial level. One example is the dynamic, variothermal temperature control that is used for example in the production of demanding micro structures [2]. Other developments have centered on improved or innovative technologies for the delivery of very small amounts of material with high levels of thermal and rheological homogeneity and the precise injection phase that follows [3]. Thus it is possible to produce even the smallest components with just a few milligrams of weight with the highest possible levels of precision.

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The Dependence of Properties on the Specimen Size

Despite the adjustments in the process technology for micro parts mostly the potential of the technical thermoplastics often used cannot be fully utilized in combination with steel molds and conventional temperature control technology. The main reason for this is increasingly rapid cooling with decreasing dimensions that is detrimental to the morphological and mechanical properties [4, 5]. High cooling rates can result in significant structural changes in the form of fine crystalline structures with a low degree of crystallization. **Figure 1** shows this for Campus and micro tensile bars (Campus tensile bar scaled down by 1:16) made from non-nucleated polyamide 66 (PA66, grade: Ultramid A3K, manufacturer: BASF SE), manufactured on an injection molding machine with a reduced screw diameter of 15 mm (type: Allrounder 370U 700-30/30, manufacturer: Arburg GmbH & Co. KG). In the core of the micro tensile bars the degree of crystallization is approx. 15 % lower than in the Campus tensile bars, which have a typical degree of crystallization for PA66 of around 40 %.

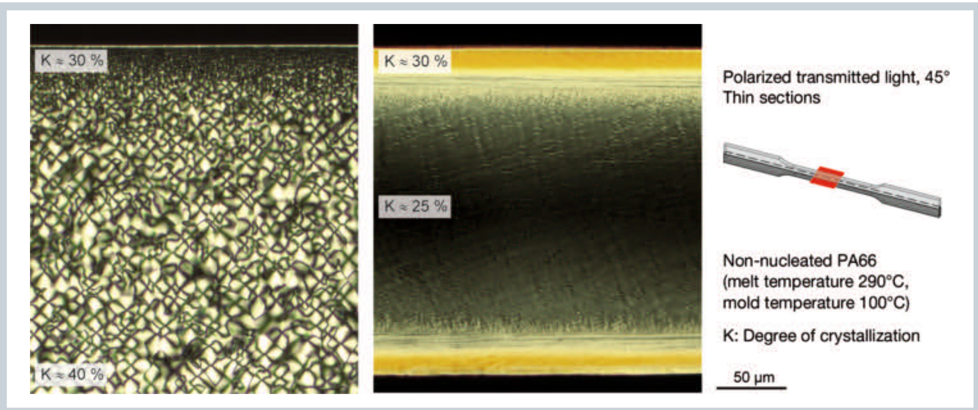


Fig. 1. Dependence of the morphology on part size for injection molded tensile bars made from non-nucleated PA66 (left: Campus tensile bar; right: micro tensile bar (1:16))

Higher flow speeds lead to an increase in the molecular orientation. Their relaxation is also influenced by the cooling rate and at the same time the flow affects the crystallization. This is seen in particular in the boundary layers. With falling part dimensions this leads here on the one hand to a reduction in crystallization due purely to cooling and on the other hand to an increase in the flow induced component. The resulting degrees of crystallization for the different sized tensile bars are at around 30 % nearly at the same level.

With the cooling dependent low degree of crystallization in the core and the high flow dependent component in the boundary layers combined with the high levels of orientation there is a high degree of inhomogeneity across the part and thus sub-optimal conditions for the in-service properties in general. This can in particular be seen in the mechanical properties **(Fig. 2)**. With decreasing size the tensile bars lose stiffness and strength and become tougher. For the smallest parts a reversal in the trend is seen that is due to the increasing flow induced crystallization. However, the detrimentally affected properties cannot be significantly improved within the boundaries of conventional injection molding even with optimized process control [6, 7].

The Influence of Choice of Material

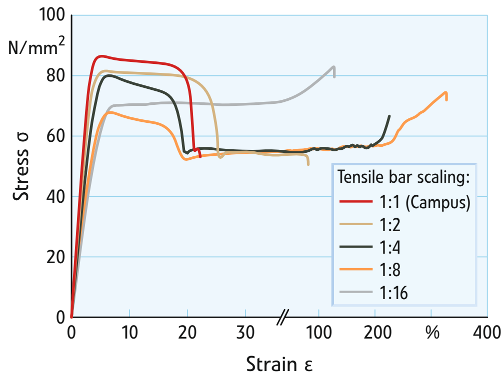
One option to achieve an adequately high crystallization over the part cross-section at high cooling rates would be to use a material for the injection molding that has a high crystallization rate. It is conceivable for example that this could be via the addition of nucleating agents or the selection of a material that simply has a high rate of crystallization. In the investigations conducted, it could be seen that the addition of nucleating agents to materials that originally had low crystallization rates and low crystallization potential such as PA66 does not lead to an increase in the rate of crystallization that could improve the mechanical properties **(Fig. 3)**.

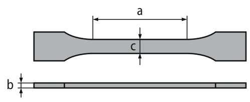
The use of the semi-crystalline thermoplastic POM, which has a high rate of crystallization and crystallization potential, however, looks advantageous. In respect of strength it is possible to achieve nearly 75 % of the material properties given by the manufacturer and the stiffness even exceeds the values for the material from the standard test specimen. It should be noted though, that the increase results in part from the higher crystallization rate and thus higher degree of crystallization and also from a surface near high level of flow induced crystallization and high degrees of orientation. Particularly the orientation leads to an undesirable directional dependence in the in-service properties. Generally it can be seen that materials with high crystallization rates and high crystallization potential should be preferred, but a possible flow dependent property anisotropy has to be considered.

Alternative Mold Materials

Active reduction of the cooling rate using variothermal temperature control with water as the thermal transmission medium has already been industrially implemented [8]. Using this concept the mechanical properties of non-nucleated PA66 can be improved in comparison to conventionally cooled small tensile test bars **(Fig. 4 left)**. Another option for optimizing micro parts is processing using low thermal conductive mold inserts, which also leads to a reduced cooling rate. By manufacturing with inserts made from zirconium oxide (ZrO_2) with a thermal conductivity of 2 W/mK similar property values to variothermal process control can be achieved. The mechanical properties of small parts produced in a PEEK insert are even significantly higher **(Fig. 4 right)**. This is due to the homogeneous structures with a higher degree of crystallization across the entire cross-section.

The benefit of slowly cooled micro parts is particularly relevant for technical components that are subjected to tribological loading in use. In comparison to parts cooled quickly in steel inserts the coefficient of friction for parts cooled slowly in PEEK inserts can be improved →





Non-nucleated PA66 (melt temperature 290 °C, mold temperature 100 °C)

	Test specimen dimensions			Test conditions	
	a [mm]	b [mm]	c [mm]	$v_{E\text{-}Modulus}$ [mm/min]	v_{break} [mm/min]
Campus-Tensile bar (1:1)	80	4	10	1	50
1:2-Tensile bar	40	2	5	0.5	25
1:4-Tensile bar	20	1	2.5	0.25	12
1:8-Tensile bar	10	0.5	1.25	0.125	5
1:16-Tensile bar	5	0.25	0.625	0.0625	3

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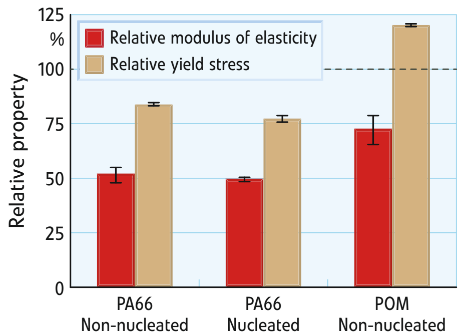
Fig. 2. Influence of part dimensions on the stress/strain behavior using the example of injection molded tensile bars made from non-nucleated PA66 (tensile test based on DIN EN ISO 527-1)



	Melt temperature [°C]	Mold temperature [°C]
Non-nucleated PA66 (Ultramid A3K, BASF SE)	290	100
Nucleated PA66 (Ultramid A3SK, BASF SE)	290	100
Non-nucleated POM (Test grade Hostaform C9021, Ticona GmbH)	230	100

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Fig. 3. Modulus of elasticity and yield stress of micro tensile bars (scaling 1:16, tensile test based on DIN EN ISO 527-1) in relation to material data given by the manufacturer (equivalent to 100 %)

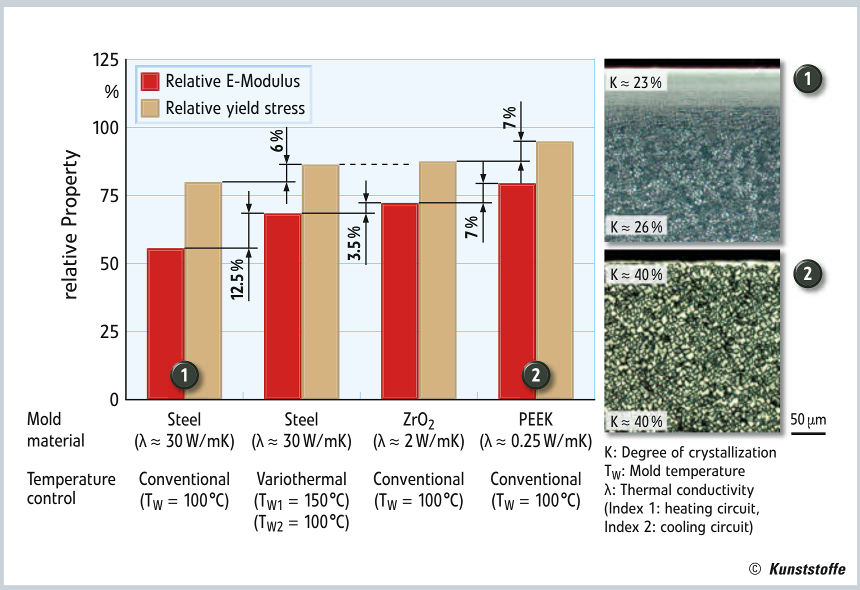

Fig. 4. Modulus of elasticity and yield stress from small tensile bars (scale 1:8, tensile test based on DIN EN ISO 527-1), made from non-nucleated PA66 (melt temperature 290 °C), produced using different temperature control concepts or in different mold materials, in relation to the material data supplied by the manufacturer

by around 25 % and the abrasion coefficient by more than 70 % (**Fig. 5**). The favorable structural properties of the slowly cooled parts can thus contribute to a longer service life or prevention of premature failure. In addition due to the significantly increased homogeneity of the structure it can be assumed that there is reduced internal stress and reduced differential shrinkage.

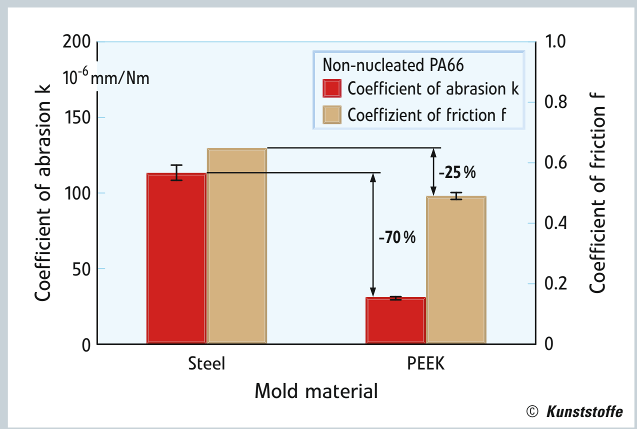

Fig. 5. Tribological properties of small tensile bars (scale 1:8) made from non-nucleated PA66, using different mold materials (pin on disc test: 1:8 tensile bar, A = 4 x 1.25 mm², sliding partner: steel, Rz = 2.6–2.8 µm, T = 23°C, p = 4 N/mm², v_{slide} = 0.5 m/s, F_N = 20 N)

Layer Model for the Prediction of Mechanical Properties

As can be seen from the results the properties of micro parts in tensile testing can obviously be related to the layer dependent structures formed conditional on the cooling and flow. It therefore seems sensible when constructing a model to split the micro parts into layers with similar internal properties (degree of crystallization, degree of orientation and size of structure) and to weight this by their relative layer share. The layer dependent properties obtained from this can then be correlated with the in-service properties, for example the mechanical properties. **Figure 6** shows this in an initial model based on the layer dependent degree of crystallization (2-layer model). Independent of the part size and the mold material used the stiffness and strength of the parts made from non-nucleated PA66 are directly dependent on the layer dependent degree of crystallization. Based on the insights gained attempts are being made to correlate simulated cooling and flow conditions with experimentally derived local properties and to incorporate these into an expanded model for predicting the mechanical properties of micro parts (**Fig. 7**).

Conclusions

When manufacturing micro parts from semi-crystalline thermoplastics poorer in-service properties in comparison to macro parts can in general be expected due to flow and cooling dependent differences. The results show that materials with high rates of crystallization and high crystallization potential have beneficial effects on the properties of micro parts. However, possible flow dependent property anisotropy also has to be considered.

The use of low thermal conductive mold materials has been found to be highly advantageous for micro parts in respect of homogeneous structures with good mechanical and tribological properties. In addition, in respect of cycle time a significant reduction can be expected in comparison to variothermal temperature control, which also allows similar improvements in properties.

The mechanical properties of micro parts made from non-nucleated PA66 could be predicted from the various degrees of crystallization over the cross-sec-

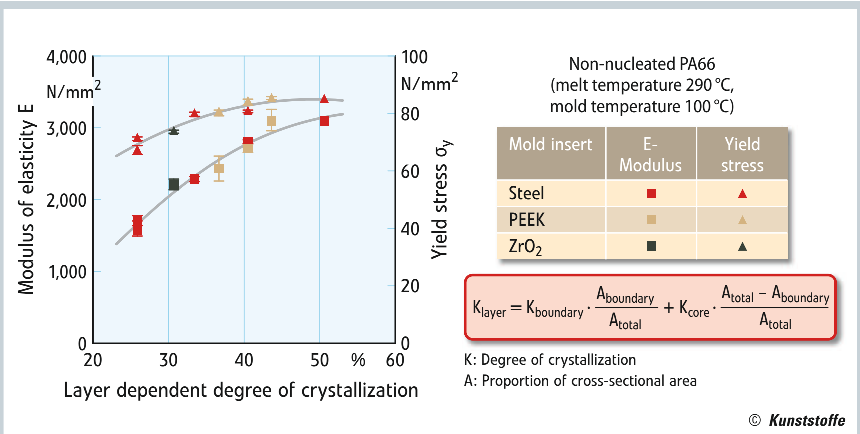

Fig. 6. Dependence of the mechanical properties on the layer dependent degree of crystallization for various part dimensions and different heat removal (tensile test based on DIN EN ISO 527-1)

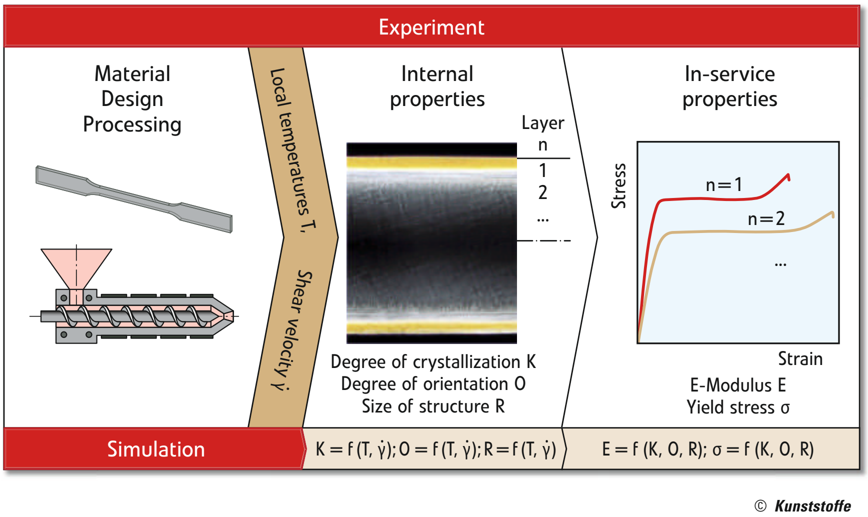

Fig. 7. Approach to predicting the material properties of micro parts

tions. The work carried out thus shows the large potential for predicting the service properties of micro parts from the flow and cooling dependent internal properties of the various layers within the part. ■

This article is dedicated to Prof. Dr.-Ing. Dr.-Ing. E.h. Walter Michaeli on the occasion of his 65th birthday and his retirement.

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