VARIANCES OF THE MECHANICAL PROPERTIES OF FILLED POLYMER MATERIALS IN A VARIATION OF INJECTION MOULDING INPUT PARAMETERS

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Continuum (filled polymer) is inhomogeneous and anisotropic. The Continuum is used in an injection moulding simulation at first (generally unnewton type of fluid). Then the continuum is solid (after cooling) and it is possible to carry out ordinary structural analysis with it. The solid continuum has different mechanical properties for each of discrete elements. A consequent stress field will generally have different values when influence of injection moulding is taken into account for analyses.

KEYWORDS

fiber orientation, injection moulding, rheology, structural analysis, FEM, mesh

1 INTRODUCTION

The essence of the analysis was multiphysics task that combines structural analysis (FEM) and analysis of injection moulding for filled polymer (glass fiber). For the analysis of injection moulding technology parameters are changed according to the statistical distribution. The results of this analysis show very surprising progressions that could not be predicted.

2 DESCRIPTION OF THE MULTIDISCIPLINARY MODEL

See the figure 1.

A) Generating of oriented mesh of elements

The analysis was performed on a rider bowden ending – see the figure 2. The rider is powered by a bowden cable and there is a counterforce on a dish. The picture shows load F = 50N and fixing of the part for a structural analysis and an injection inlet (for an injection moulding analysis) is also shown, the range where a mould cavity is filled. The material chosen for the analysis was POM-GF30, especially HOSTAFORM C 9021 GV1/30 by the TICONA producer.

B) Determination of input parameters using the Monte Carlo method

They were set variables that are subjected to variation. In our case it was the injection pressure, melt temperature and mould temperature, in which the melt (filled polymer) is injected. It is appropriate to analyze the influence of individual variables using tools DoE (Design of Experiments). It was found that any of the factors is negligible. These factors are subsequently changed (due to the Monte Carlo method) according to a given distribution.

C) A random number generator

The change of the input parameters was performed through random number generator in the form:

$$x_{n+1} = (1375x_n + 97531)(mod\ 1234567890) \qquad (1)$$

D) An Injection moulding simulation

The oriented mesh was generated first in Mentat with an element size 0.3 mm (see the figure 3). This mesh was (orientation included) imported into Moldex3D (see the figure 4) where the mesh for injection inlet was also modeled. After performing the initialization simulation, the mesh and material characteristics with a reduction were re-imported into Mentat again.

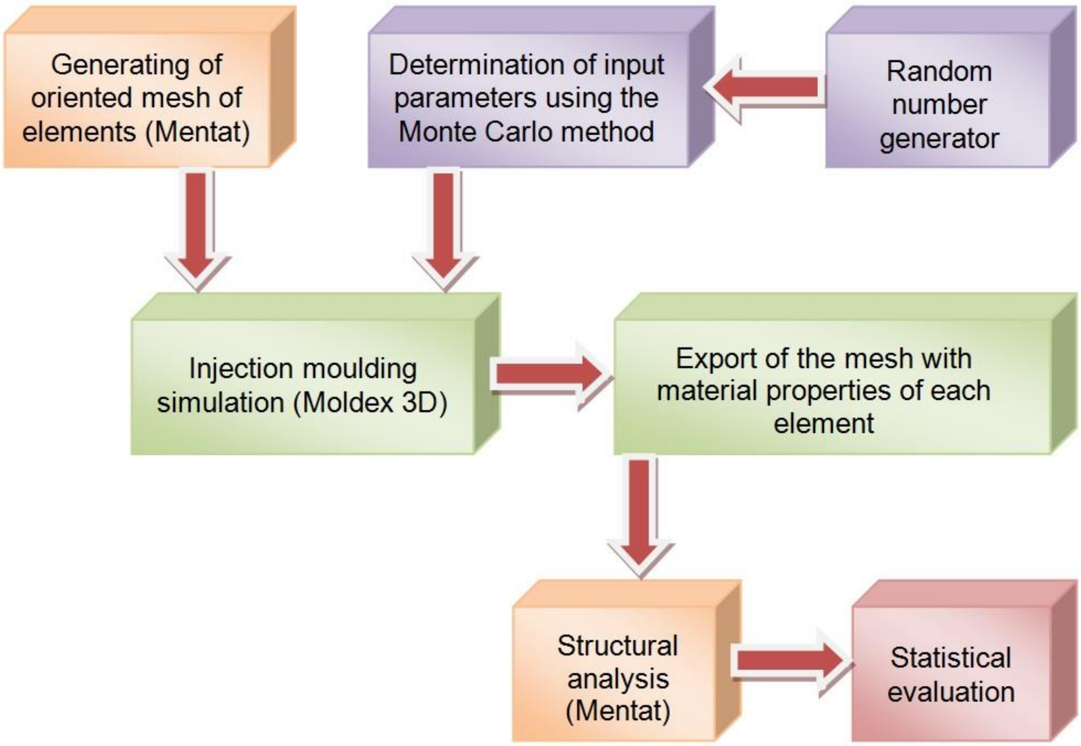

Figure 1. Multidisciplinary model assembling

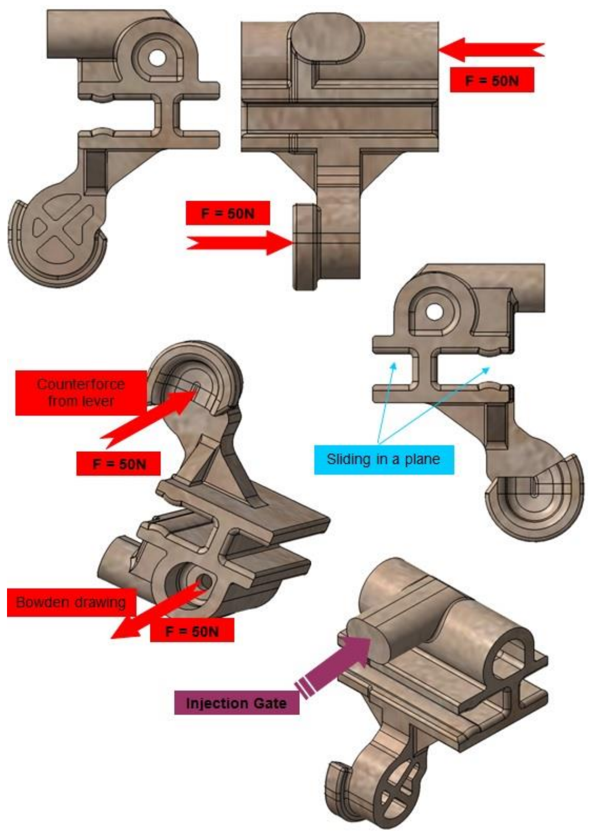

Figure 2. The rider of Bowden ending

Figure 3. Oriented mesh

E) Export of the mesh with material properties of each element

As shown in the figure 4 Mentat loaded 354,804 elements and 35,537 material groups (material properties). The number of materials was therefore reduced to about one tenth. That means that roughly every 10th element has its unique material properties. The figure 5 shows the elements with material characteristics. However, as the color range is limited to 32 variations of colors, nothing could be seen on the model, so it was done detail of the distribution of material groups around a portion of the hole. On this detail it is clearly evident that almost every element has its own material characteristics. Let us point out the reasons why we reduced the number of materials and why we did not create a full export of material properties for each element. Full conversion was performed but it turned out that the mesh export from Moldex lasted for about 1.5 hours and the import into Mentat took incredible 10 hours! If we add a time for the analysis of injection moulding process and for the structural analysis we get to number about 12 hours per test. These are significant time costs. This time has to be multiplied by the number of performed iterations (the number of analyses with different technological parameters). This leads to a number from 1.000 to 2.000 hours of computing time! To be able to make our desired summary analysis (hundreds) a reduction of material groups is required. Time per analysis is thus shortened from about 12 hours to 1.5 hours. So we have reduced the required processing time about 10 times.

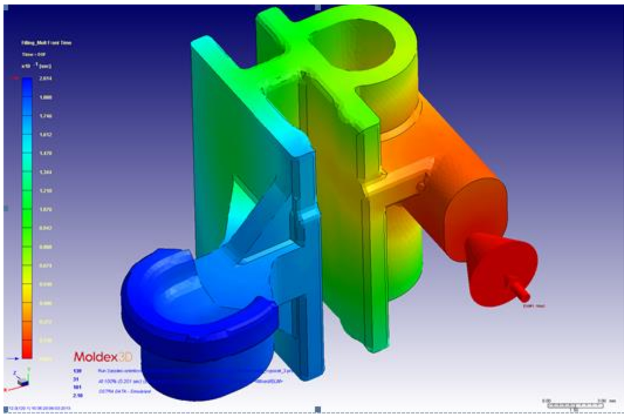

Figure 4. Model with the injection inlet

F) The structural analysis and the statistical evaluation

Finally, a calculation was carried out taking into consideration the orientation of glass fibres. The results were very surprising. After determining the set of input technological parameters it was finally possible to perform the analytical experiment. That, as we mentioned, was very time consuming and produced data reached relatively high level – 140 GB. Each experiment has its own unique combination of input factors. For each unique set of input parameters response (stress) at 4 selected points (see the figure 6) was observed.

3 CONCLUSIONS AND RESULTS

As we know, the results should have a statistic character. In order to make the results of a statistical sample relevant, 256 experimental analyses were performed. Of course, it is expected that for an increasing number of analyses the statistical distribution of results converges to the exact solution.

The resulting data are processed into graphs in figures 7 and 8, which are actually the output of our previous efforts, and now they will be explained. Let's start with the red line in the graphs histograms of frequency response of stresses (figure 7) with the legend "homogeneous material". First an analysis with homogeneous material had been performed (i.e. without considering fiber orientation). For so-defined material the following responses in defined points were received:

- the stress is 61.56 MPa in the point 1
- the stress is 38.02 MPa in the point 2
- the stress is 55.57 MPa in the point 3
- the stress is 37.81 MPa in the point 4

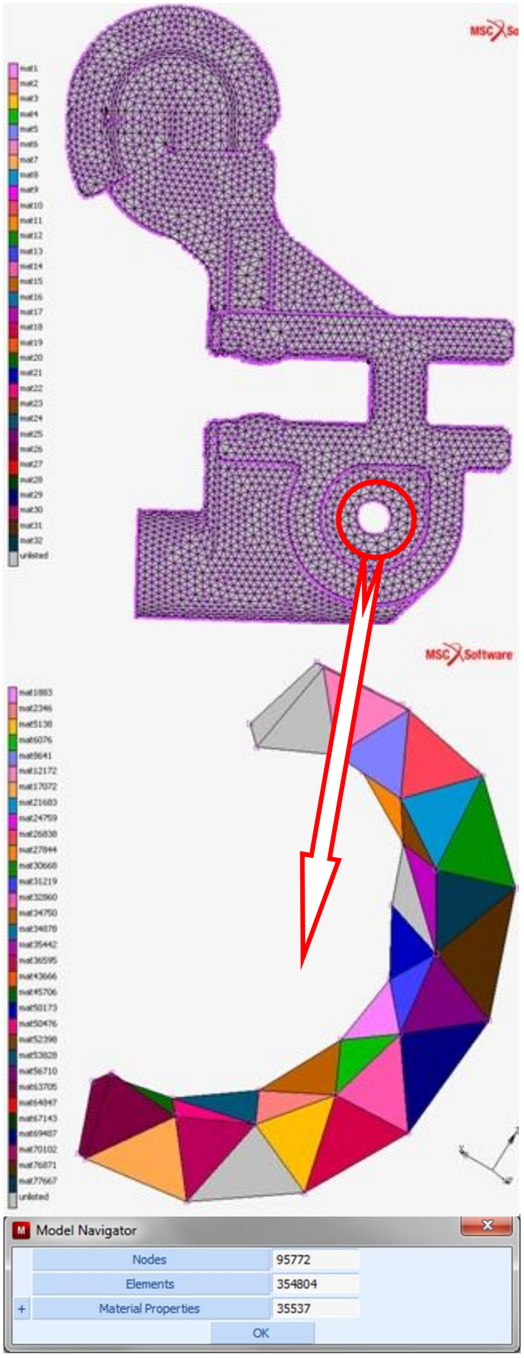

Figure 5. Export of the mesh with material properties of each element

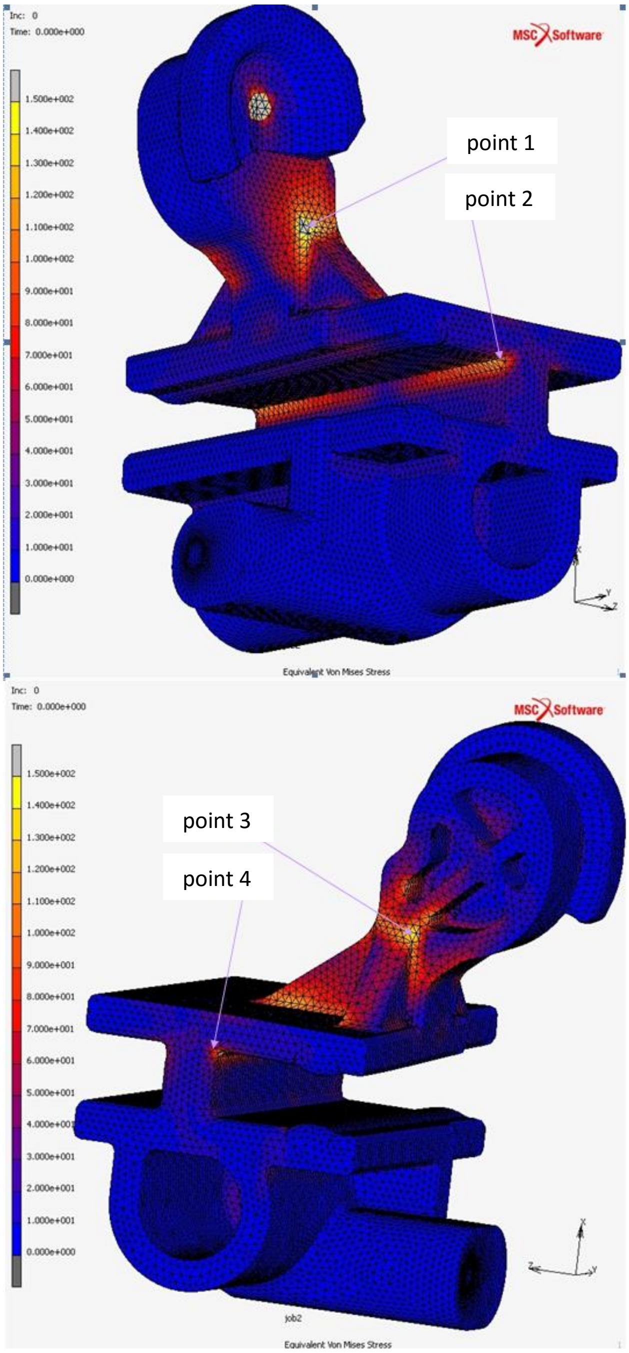

Figure 6. Stress fields and the points where the response was measured

This way would therefore look stress, we performed linear structural analysis of homogeneous material. From the graphs it is immediately apparent that a stress without considering the orientation of particles is systematically lower with the exception of response of the stress in the point 3 where it corresponds exactly to the center of distribution of stress considering the orientation of filled particles. This leads to the first important conclusion, namely that **the structural calculation of homogeneous material shows a systematically lower level of the stress than there really is in the reference point and a risk of destruction is thus in fact underestimated**.

Now we have an explanation of the important function of the red line for a homogeneous material, and we can continue to describe the graphs of frequency that were created from graphs of points distribution on the figure 7. From the frequency distribution it can be estimated that for an increasing number of analyses the trend of frequencies would probably converge to a curve of normal distribution. This trend is evident in all four monitored graphs and it is even shown by the red curve of approximation, which is connected to the charts (see the figure 8). The polynomial regression of the 4th order was used for this trend curve. This frequency distribution could be expected because input technological parameters were also selected along the pattern of the normal distribution, and this assumption was indeed confirmed. Each "overlaps" and "teeth" from "ideal" approximation functions are evidently caused by a relatively small number of experiments - even if it seems that number of 256 experiments is relatively high, it is estimated that the for extermination of these deviations would be required experimentation by one order more. Another factor that may distort the frequency distribution is the choice of the width of the intervals (classes). Inappropriate choice can lead to underexposure or overexposure of frequencies. The value 1MPa has been chosen as a unit for width of interval for all histograms. While the frequency distributions along the lines of the normal distribution were expected, considerable variability in stress of continuum definitely surprises. Note that the input parameters are only changed in the range of + 10% of the nominal value (the injection pressure, melt temperature and mould temperature). But an output response varies in much wider bands. When the middle value of each histogram is taken as a nominal value then we get a range of bandwidths responses:

- the response range in the point 1 is 67.5 MPa + 10.5 MPa ≈ 67.5 MPa + **16%**

- the response range in the point 2 is 45 MPa + 9 MPa ≈ 45 MPa + **20%**

- the response range in the point 3 is 54.5 MPa + 9.5 MPa ≈ 54.5 MPa + **18%**

- the response range in the point 4 is 46 MPa + 13 MPa ≈ 46 MPa + **28%**

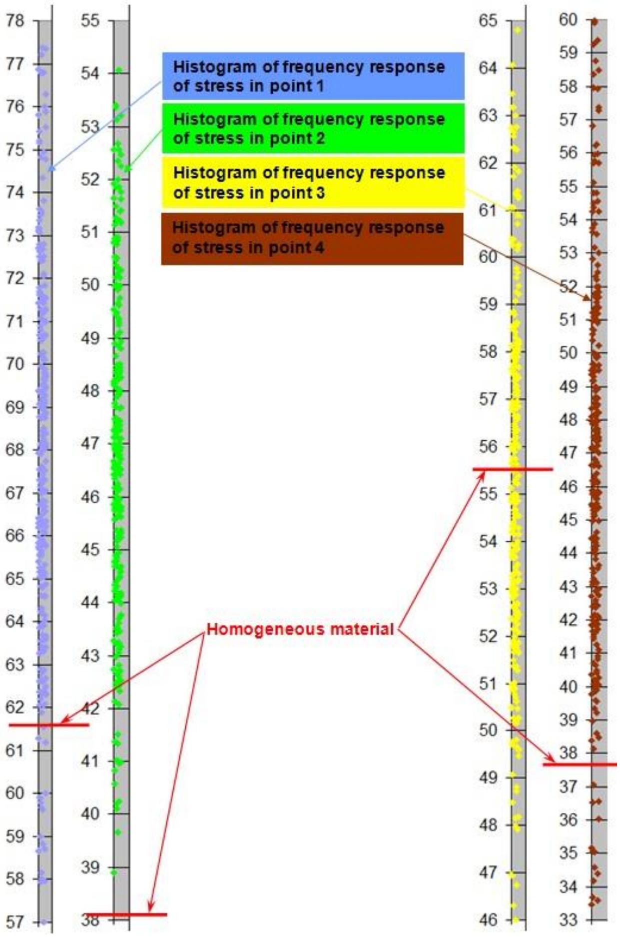

Figure 7. Histograms of frequency responses of stress in each surveyed points

It follows that the variation of the input process parameters of injection moulding of 10% brings a variation of the stress response in twice average range, namely **20.5%**! It certainly was not an expected result. These results suggest that the effect of fiber orientation has more fundamental influence on the stress field than the input technological parameters, but it should be understood that the orientation of particles is very dependent on these input parameters.

Look at facts that follow from cumulative frequency analyses of stress in given points now. Above all, it is clear from the graphs that the vast majority of values of stress is above values for homogeneous material. Specifically, for individual responses:

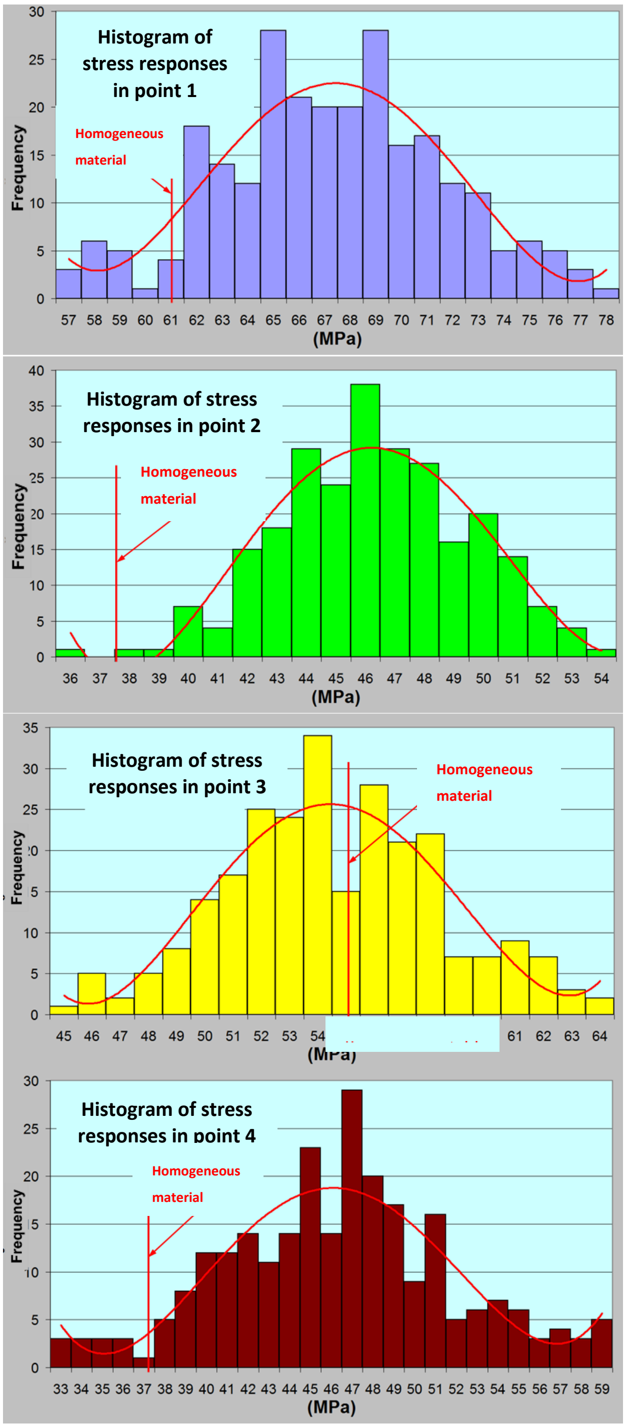

Figure 8. Histograms of frequency responses of stress in each surveyed points

- for the point 1 238 values are above the line for homogeneous material, which is **92.97%**.

- for the point 2 255 values are above the line for homogeneous material, which is **99.61%**.

- for the point 3 111 values are above the line for homogeneous material, which is **43.36%**.

- for the point 4 243 values are above the line for homogeneous material, which is **94.92%**.

On average, therefore **83%** of values are above the value of stress for homogeneous material. This is certainly a significant number, indicating that stress is actually underestimated.

However, this does not necessarily mean a smaller strength because the orientation of the particles may be beneficial and may even increase the strength with comparison to homogeneous materials. For the criterion of the strength we would have to evaluate strength parameters for each element itself. In any case, the difference from the homogenous material is unexpectedly high. It is assumed, however, that differences will be smaller toward the center of the material (and thus to the middle of material flow), because the orientation dependence on the mould temperature will be lower – "information" about mould temperature is not simply able "to arrive" to middle of the material in given time.

Let´s return now to the histograms (and hence cumulative frequencies) in terms of an idealized normal distribution and express them as a formula and by graphs, for example, to set limits 3σ and optionally limits of ppm. Consider approximation curves on the figure 8 as a basis. The curve height *a* can be determined in the center of curve (in place of μ). Furthermore, it is known that the graph has got a width at half of height $2\sigma\sqrt{2\ln 2} \approx 2.3548\sigma$. From that the parameter σ can be determined. The values for idealized states are then sorted in the following table:

Stress response in point	*μ*	*a*	*σ*
1	67.5	22.5	4.67
2	46.2	29.5	3.82
3	54.4	25.8	4.20
4	46.1	18.7	5.50

Table 1. Idealized parameters of the normal distribution for each response

Individual functions can then render substituting into the following formula:

$$f(x) = ae^{-\frac{(x-\mu)^2}{2\sigma^2}} \geq 0 \qquad (2)$$

Note that the parameter μ is both an expected value and a median, parameter σ is a standard deviation and value σ^2 is a variance.

If we have the distribution function, we can determine ppm of cases of specific stresses and even those (extremes) that our statistical sample of 256 measurements has not affected. For example, for the stress in the point 1 the limit maximum value is 78 MPa (figure 7) in the experiment, but the figure 9 clearly shows that for an increasing number of measurements the range of maximum stress would extend up almost to the limit of 90 MPa. It follows from the graph that statistically 1 part per million (1ppm) would have stress 90 MPa in the response point 1, 10 parts per million (10ppm) would have stress 87 MPa, 100 parts per million (100ppm) would have stress 85 MPa, etc. Summary of ppm is expressed in the table 2, where there are also values of stress of homogeneous material for comparison. This covered completely all significant quantities of our experiment. This chapter can be closed by saying that **the experimental results (their distribution respectively) surpassed all expectations concerning the extension of results variance and the size of stress in comparison to the structural analysis for the homogeneous material**.

ppm	*Point 1 [MPa]*	*Point 2 [MPa]*	*Point 3 [MPa]*	*Point 4 [MPa]*
1	90	64	74	72
10	87	62.5	72	69.5
100	85	60.5	70	66.5
1,000	82	58	67	63
10,000	78	55	64	59
100,000	73	51	60	53
Homogeneous material	**61.6**	**38**	**55.6**	**37.81**

Table 2. ppm for stresses in given points of examined response

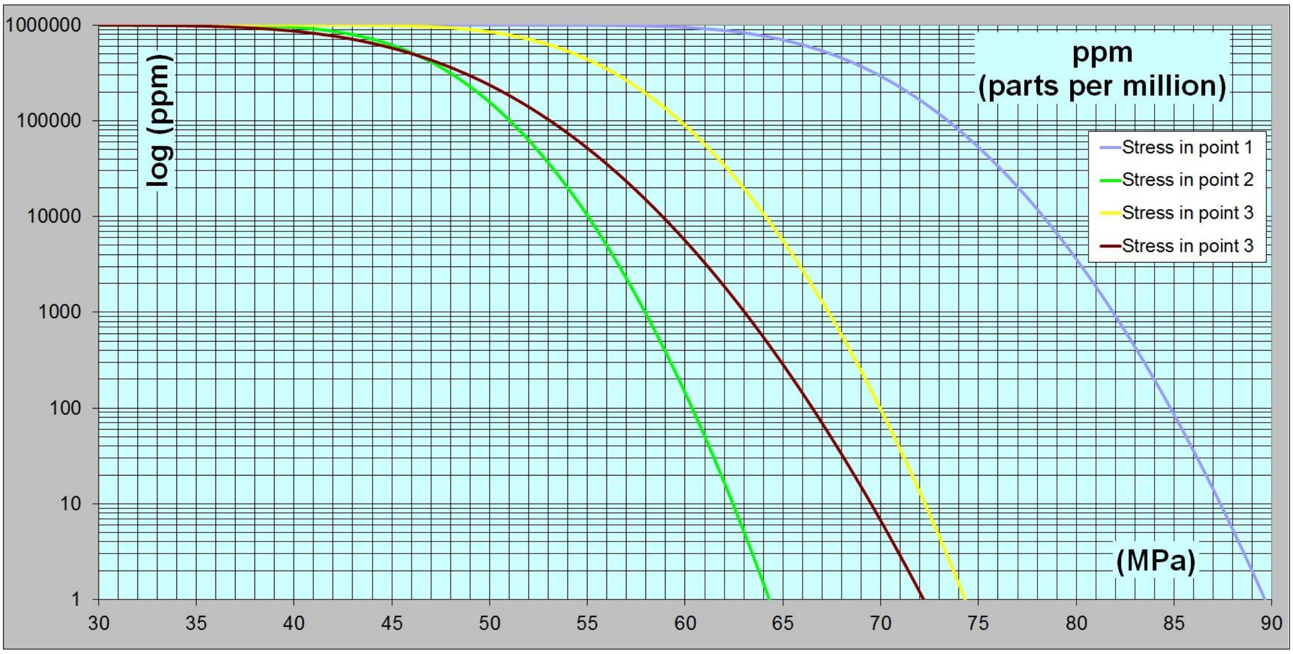

Figure 9. ppm for stresses in given points of examined response

REFERENCES

[Babatubde 2011] Babatubde O. A., David A. J. Observed deviations between classical and novel mathematical models for predicting fiber orientation in injection molded composites. 2011 ECTC proceedings ASME early career technical conference hosted by ASME district E and University of Arkansas. 2011.

[Bird 1987] Bird, R. B., Armstrong, R. C., Hassager O. Dynamics of polymeric liquids. 1987. ISBN 0-471-80245-X.

[Jin 2010] Jin, W., Xiaoshi J. Comparison of recent fiber orientation models in Autodesk Moldflow Insight simulations with measured fiber orientation data. Proceeding of the Polymer Processing Society 26th Annual Meeting, Banff (Canada) PPS-26. 2010.

[Juang 2004] Juang, Y. J., Wang S., Hu X., Lee L. J. (2004) Dynamics of Single Polymers in a stagnation flow Induced by Electrokinetics 2004, Phys. Rev. Lett. 93, 268105.

[Miled 2011] Miled H., Silva L., Coupek T., Agassant J.-F. Injection moulding of fibre reinforced thermoplastics: integration of fibre orientation and mechanical properties computations. 27th World Congress of the Polymer processing Society, Marrakech : Morocco. 2011.

[Sillem 2010] Sillem A. Fundamental Theory and implementation of the Wang-O´Gara-Tucker model for the modeling of fiber orientation in fiber filled injection molded thermoplastics. MSC thesis mechanical engineering, Delft University of Technology, 2010.

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