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# MANUFACTURING MACHINE RESEARCH WITHIN THE FRAMEWORK OF RESEARCH PLAN SUB-PROJECT

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## 1. Introduction

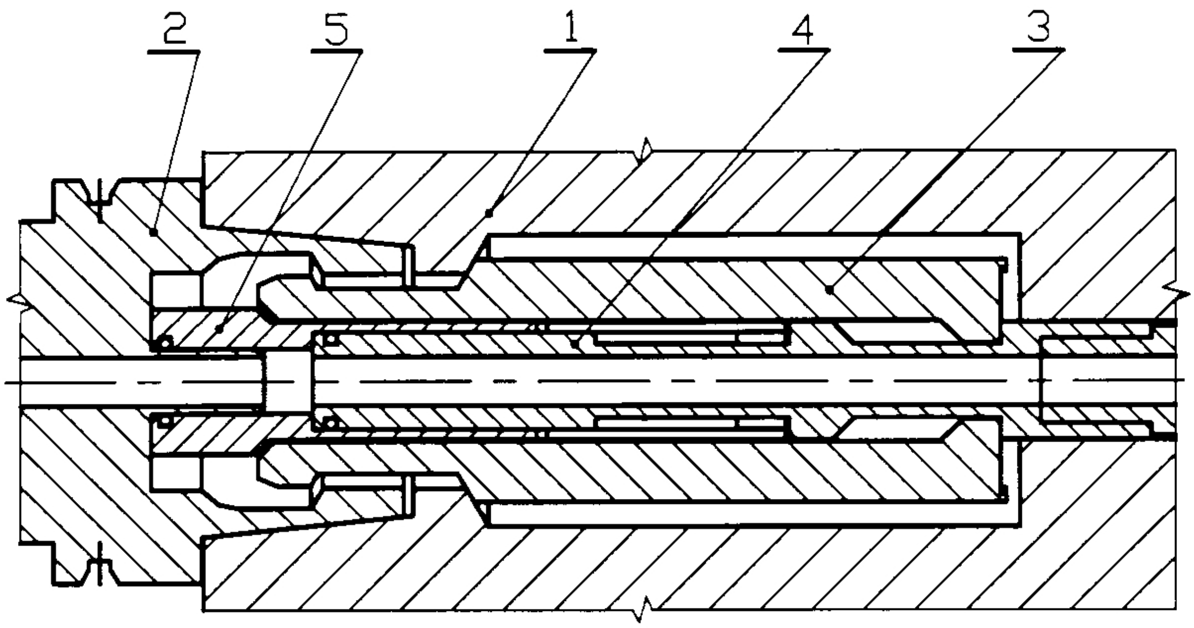
The sub-project of research plan MSM 232100006 'Innovations, Engineering Design, Technology and Material Engineering of Industrial Products' has been carried out at the Department of Machine Design in years 1999 – 2004. It is focused on machine elements, machine tools and forming machines. This paper deals with the results achieved in the area of machine tools and forming machines, i.e. manufacturing machines.

## 2. Machine tools

### 2.1 Research and development of new clamping device concepts

In the area of machine tools during the first years of the research plan the actual content of the research work was crystallized, as is evident from research papers undertaken during the first years of the research plan. The focus has been chiefly concentrated on research and development of new clamping device concepts, which could be suitable for High Speed Cutting (HSC).

Firstly a new concept for a tool clamping device for HSC, using the deformation of gripping elements for induction of clamping force, has been designed. The deformation is driven by a linear hydro motor, however rotational pressure oil feeds are not necessary. The clamping safety is higher, because the clamping force is maintained even during mains failure and following the decline of pressure in the hydraulic system. The device does not cause imbalance of the spindle and is able to eliminate the inaccuracy of hollow tapered shanks (HSK). The clamping device is shown in Figure 1 and Figure 2.




**Legend: 1 – spindle, 2 – HSK clamping taper, 3 – gripping elements,**
**4 – drawbar, 5 – take up tube**

**Figure 1. Tool clamping device for HSC – before clamping**

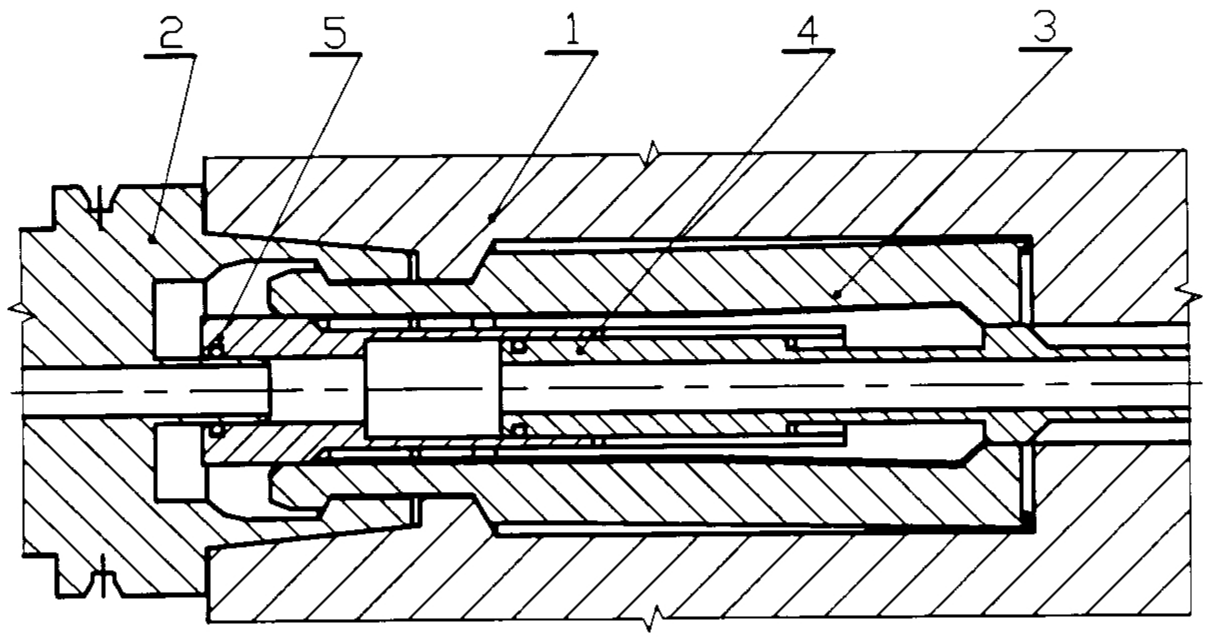



**Figure 2. Tool clamping device for HSC – tool clamped**

During further research an advanced concept of the tool clamping device was designed. In this advanced design concept the clamping force is inducted by means of a self-locking mechanism, which is driven hydraulically, however the design has been carried out so that the rotated parts (placed in the spindle) of the clamping mechanism are detached from the non-rotated parts (placed in the headstock). This concept achieves minimal costs of device operation and maintenance. Positions of all mechanism parts placed in the spindle are ensured against spatial position change, thereby ensuring that after balancing the clamping device imbalance cannot occur. The clamping device also enables elimination of the inaccuracy of HSK; this means that clamping force is constant and independent from the actual size value within HSK tolerance range (similar to hydraulic-mechanic systems). Research and development of these clamping devices resulted in submission of two patent applications 'Tool clamping device for machine tool spindles' [Navara, Stadler, Lasova and Kratky 2002] and 'Tool clamping device for HSK and its usage' [Novak 2003].

## 2.2 Research into unconventional material applications

During the following years the focus has been concentrated on unconventional material applications on machine tool design. It chiefly deals with material based on fibre composites, whose utilization is still not common in this area, but considering the mechanical properties of these materials and continuously decreasing costs it is possible to expect growth of demands for suitable applications of composites into machine tool design. Composite material mechanics makes slightly higher demands on engineering designers and computational engineers, and so the goal of participants in the research plan was to build up and experimentally verify suitable numerical simulations of composite materials and their mechanical behaviour. For this reason in years 2002 – 2004 experiments with wound composite tubes were performed, which were stressed simply by tension, bending and torsion, their deformation has been measured and stiffness determined depending on composite fibre direction and their layer thicknesses. At the same time numerical simulations of these testing specimens were under way in an effort to find suitable methods of realistically modelling the composites in Finite Element Method (FEM) software system environment, e.g. ANSYS. The specimens were prepared by fibre winding method. The matrix and fibre properties were provided by the specimen producer and these are stated in Table 1.

**Table 1. Matrix and fibre properties**

| property | matrix | fibre |
|---|---|---|
| Modulus of elasticity in tension *E* [MPa] | 3200 | 235 000 |
| Modulus of elasticity in shear *G* [MPa] | 1600 | 5000 |
| Poisson's ratio $\nu$ | 0.4 | 0.3 |
| Density $\rho$ [kg /m$^3$] | 1200 | 1750 |
| Voluminal portion *V* | 0.45 | 0.55 |

All specimens have been made with internal diameter D = 26 mm and length l = 210 mm. The external diameter depends on layer thickness t, which is calculated in connection with fibre winding angle according to the relation (1):

$$t = 0.5\left(\sqrt{\frac{8A_f N}{\pi V_f \cos\varphi} + D^2} - D^2\right) \tag{1}$$

where:

$A_f$ … fibre cross-section [mm$^2$]
$V_f$ … fibre voluminal portion
N … number of needles over mandrel circumference
D … internal tube diameter [mm]

Nine different fibre laying angles with different layer thickness have been used, and it has always been used with double-layer symmetrical laminates. Concrete values are stated in Table 2.

Table 2. Fibre laying angles and layer thickness

| no. | winding angle + / - [°] | layer thickness [mm] |
|---|---|---|
| 1 | 7 | 0.495 |
| 2 | 10 | 0.498 |
| 3 | 14 | 0.506 |
| 4 | 17 | 0.513 |
| 5 | 20 | 0.522 |
| 6 | 26 | 0.545 |
| 7 | 31 | 0.571 |
| 8 | 36 | 0.605 |
| 9 | 46 | 0.702 |
| 10 | 59 | 0.938 |

For material module of ANSYS system it is necessary to enter for orthotropic material the values of one longitudinal and two cross moduli of elasticity in tension, a further three values of modulus of elasticity in shear and three values of Poisson's ratio. These values have been determined with the use of formulae from professional literature.

The computational model is fixed on one side and on the other side radially it is guided and stressed by tensile force. These boundary conditions correspond well to specimen clamping and stress in the tensile testing machine. One of the computational models with displayed boundary conditions is stated in Figure 3.

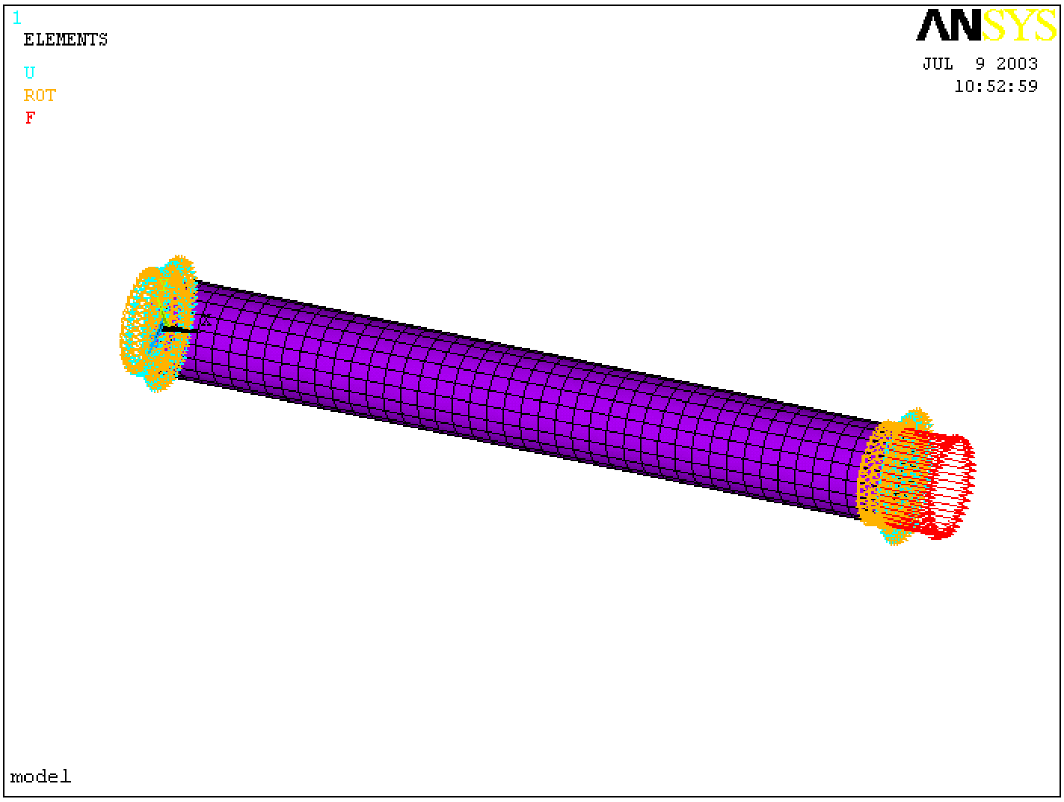



**Figure 3. One of the computational models with displayed boundary conditions**

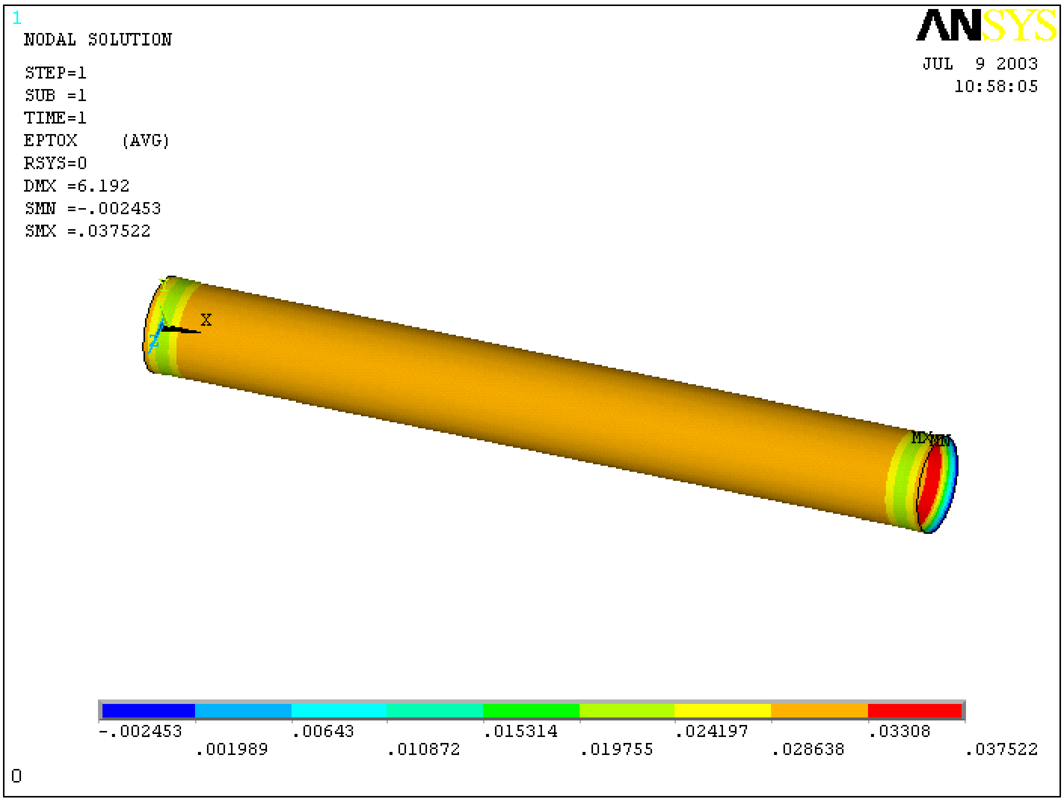



**Figure 4. Illustration of the results**

For the comparison of computed and measured results the effective Poisson's ratio $\nu_{xy}$ has been evaluated, i.e. strain ratio $\varepsilon$ in direction x and y and further effective modulus of elasticity in tension $E_{ef}$. Because measurement has been repeated several times for each winding angle, the average value of acquired values has been used for comparison.

The comparison of computed and measured effective Poisson's ratios $\nu_{xy}$ is stated in Figure 5. and the comparison of computed and measured effective modulus of elasticity in tension $E_{ef}$ is stated in Figure 6.

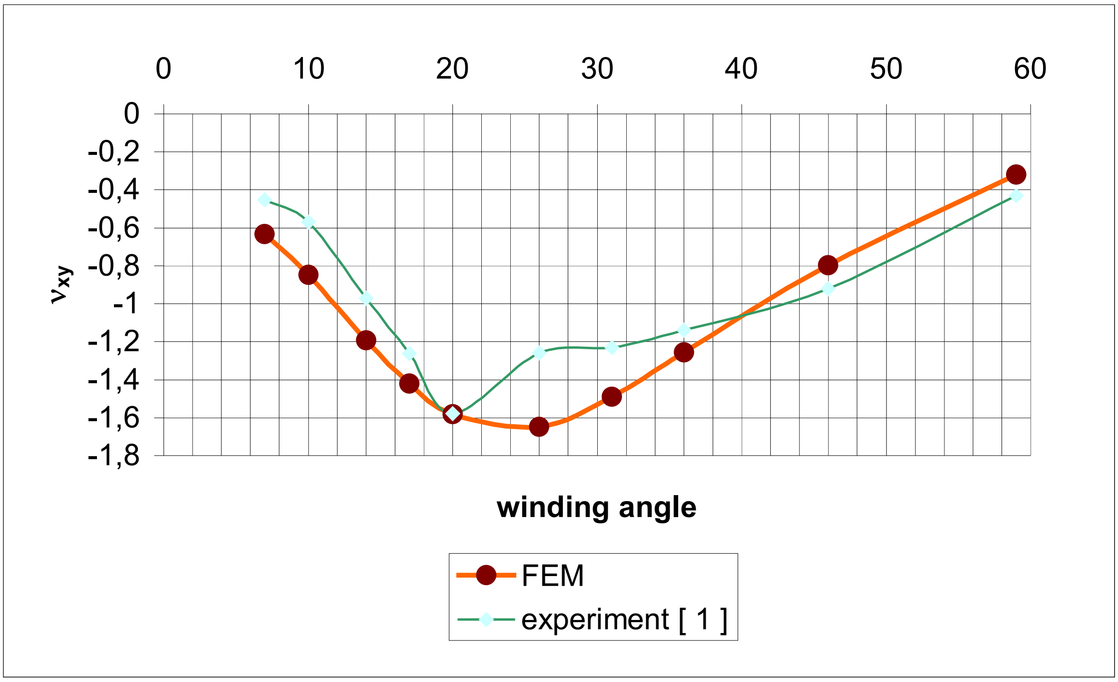



**Figure 5. Comparison of computed and measured effective Poisson's ratios**

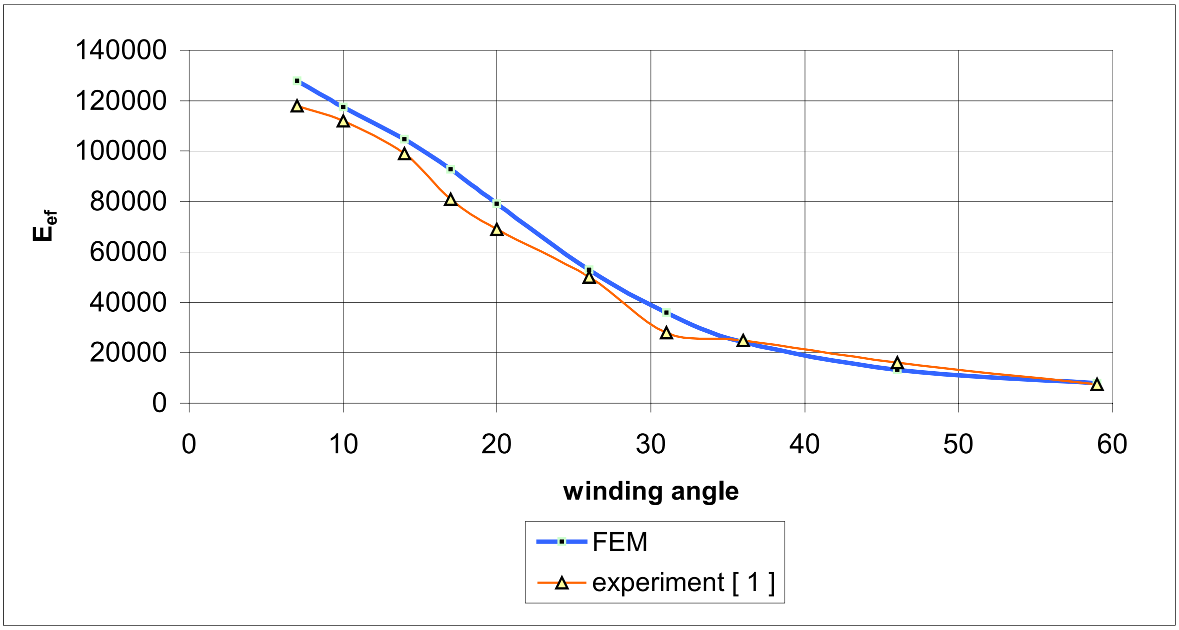



**Figure 6. Comparison of computed and measured effective modulus of elasticity in tension**

Computational procedure verification of composite tube modelling has been performed many times with different types of basic stresses, and results have been published at conferences several times, e.g. [Lasova and Stadler 2003].

Because comparison of computational procedures has been satisfactory, some applications of substitution of metal parts by unconventional material ones have been tested, chiefly at machine tool attachments.

The frames of machine tool attachments have been the subject of the first practical application of composite materials in machine tool design, e.g. additional milling equipment with long reach and boring bars for heavy-duty lathes, where the slenderness ratio is also very unfavourable. High stiffness, low mass and high dynamic stability is required from these devices.
Boring bars for heavy-duty lathes are possible to model as fixed beams and so the comparison of beam end deflection and natural frequencies of metal model and models from designed laminate has been performed. The same input values of material constants have been used for laminate as in the case of the test specimens. A bar of length 1.8 m and external diameter 60 mm, fixed at one end has been chosen for computations.
The values computed for a steel model and for three models of composite tube are stated for comparison in Table 3. For these the basic sizes are the same as for the steel model, i.e. length, external diameter and web thickness. The laminate models differ in the number of layers and in the fibre angle. The loading is only bending from its own mass.

**Table 3. Comparison of masses, beam end deflections and natural frequencies**

| **material** | **steel** | **40 layers, fibres + / - 7 [°]** | **33 layers, fibres + / - 31 [°]** | **20 layers, fibres + / - 59 [°]** |
|---|---|---|---|---|
| Web thickness [mm] | 20 | 20.4 | 19.5 | 19.4 |
| Mass [kg] | 53 | 10 | 9.9 | 9.9 |
| End deflection [mm] | 1.04 | 0.306 | 0.607 | 1.099 |
| Natural frequencies [Hz] | 19, 119, 329 | 35, 193, 298 | 24, 120, 317 | 18, 68, 158 |

The comparison shows that suitably wound laminates exhibit much higher stiffness than steel tubes. If the layers and angles are less suitably arranged for certain kind of stress, the acquired values of stiffnesses can be poorer than steel tubes. The laminates with low fibre winding angles against axis show almost double the first natural frequencies of steel and of specimens with high angles.
The results acquired for models of a tube with low fibre angle and for different numbers of laminate layers are described in Table 4. The loading is only bending from own mass again. For this loading the fibre direction is crucial, the influence of layer number is low.

**Table 4. Comparison of masses, beam end deflections and natural frequencies**

| **material** | **steel** | **40 layers, fibres + / - 7 [°]** | **20 layers, fibres + / - 7 [°]** | **10 layers, fibres + / - 7 [°]** |
|---|---|---|---|---|
| Web thickness [mm] | 20 | 20.4 | 10.2 | 5.1 |
| Mass [kg] | 53 | 10 | 5 | 2.2 |
| End deflection [mm] | 1.04 | 0.306 | 0.34 | 0.35 |
| Natural frequencies [Hz] | 19, 119, 329 | 35, 193, 298 | 33, 188, 245 | 33, 187, 238 |

The results for spatial bending from own mass and from cutting force 100 N, acting in a horizontal plane perpendicular to the tube axis, are stated in Table 5.

**Table 5. Comparison of total beam end deflections and stiffnesses**

| material | steel | 40 layers, fibres + / - 7 [°] | 20 layers, fibres + / - 7 [°] | 40 layers, fibres + / - 31 [°] | 33 layers, fibres + / - 31 [°] |
|---|---|---|---|---|---|
| Web thickness [mm] | 20 | 20.4 | 10.2 | 23.6 | 19.5 |
| Mass [kg] | 53 | 10 | 5 | 12 | 9.9 |
| Total end deflection [mm] | 1.17 | 0.84 | 1.81 | 0.89 | 1.72 |
| Stiffness [N/mm] | 85.4 | 119 | 55.2 | 112.3 | 58.14 |

In this case both fibre direction and number of laminate layers have influenced the resulting deflection. The results from Table 5 are graphed in Figure 7.

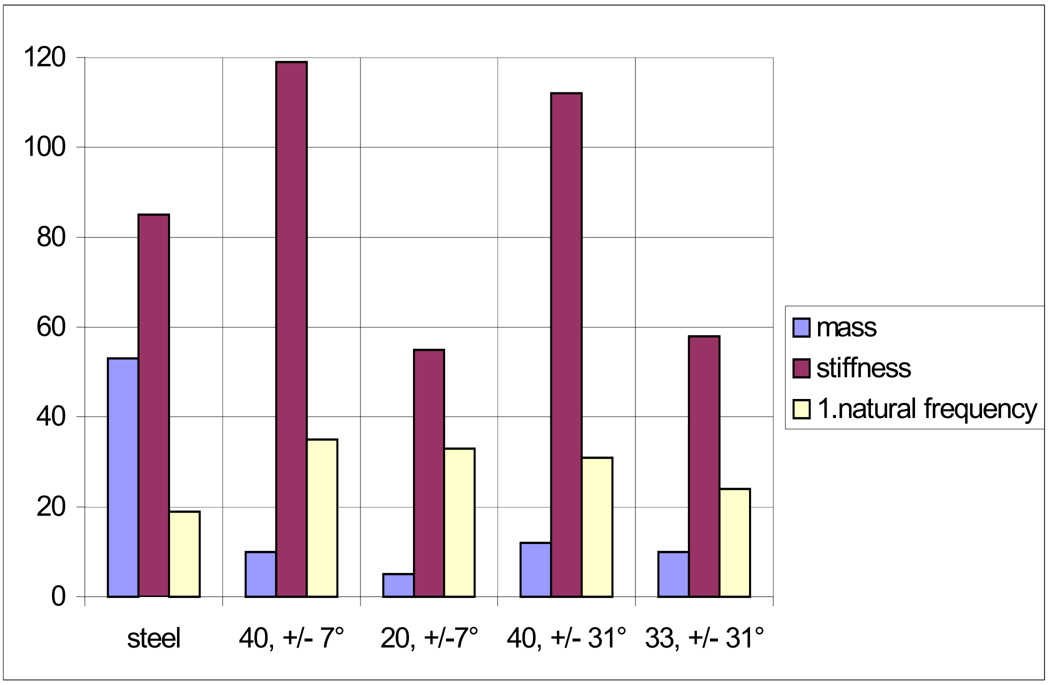



**Figure 7. Comparison of mass, stiffnesses and natural frequencies**

Substitution of milling equipment body by composite tube has been explored as a further application of composite materials [Sedivy 2004]. The computational model is shown in Figure 8.

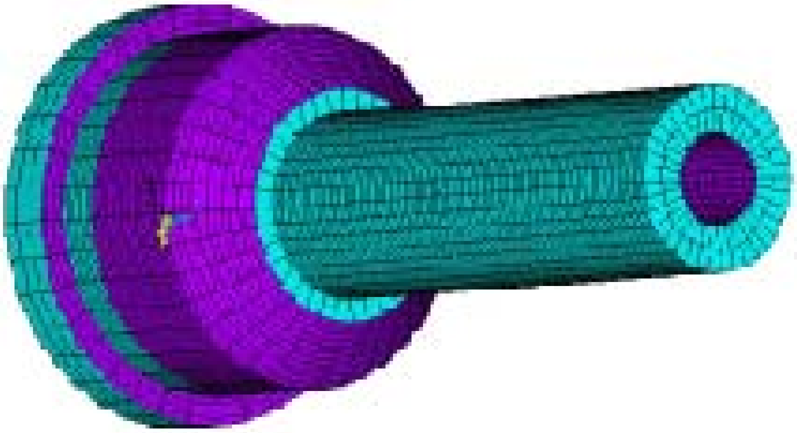


**Figure 8. Computational model of milling equipment body**

Mass has been slightly reduced and at the same time stiffness has been enhanced by about 22 % compared to steel milling equipment body by using the carbon composite for the most stressed part.
For lengthening pieces of boring equipment, which also have considerable reach, the crucial property is low mass and high stiffness along with dynamic stability, and so a further explored possible substitution has been a laminate tube instead of a complicated welded construction. The computational model is shown in Figure 9.

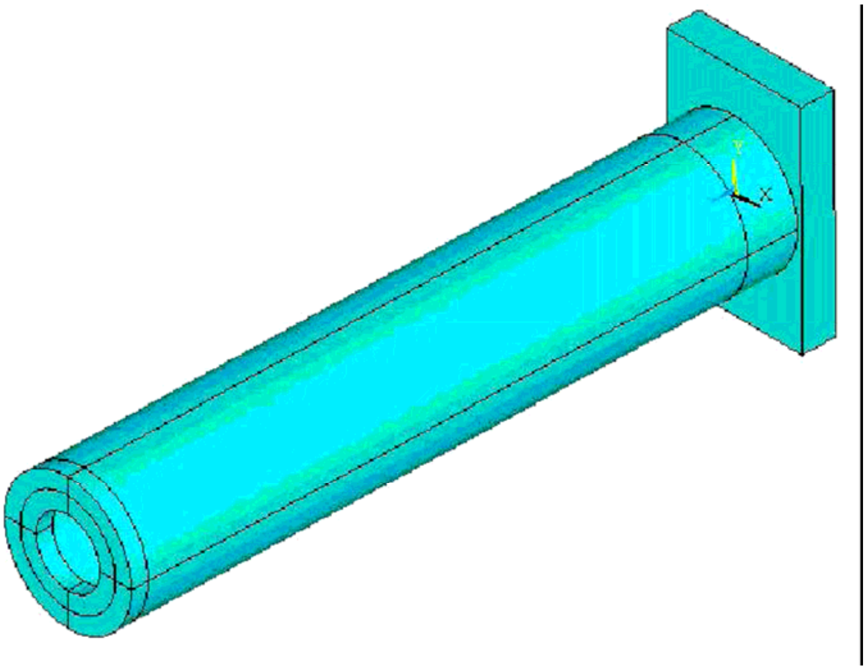


**Figure 9. Computational model of lengthening piece of milling equipment**

The quantity, which mostly restricts the frame mass, is moment of gravity forces related to the clamping surface. For steel welded construction the moment is 72 150 N/m and mass 3 700 kg, for composite lengthening piece the moment has been reduced to 38 000 N/m (by 47 %) at mass 2 400 kg (decrease of 35 %) [Sedivy 2004].
It is evident, that with appropriate composition of the laminate for certain types of external loading it is possible to achieve much better mechanical properties of the explored construction. Of course, this unconventional material application into manufacturing machine

design and the high price of these materials is still an obstacle and there are other problems, which need to be solved, e.g. joints of unconventional material and metal parts of machines.

### 2.3 Machine tools – future work

Work in the area of unconventional materials has been supplemented by research of properties and computational modelling of sandwich structures, e.g. structures filled by metal foams or honeycombs. Research of these structures, chiefly their dynamic properties and utilization of their damping capabilities in machine tool design, could be continued in the subsequent research plan.

## 3. Forming machines

### 3.1 Research and development of crank presses

In the area of forming machines significant focus has been paid to their frames. In the first years the possibilities of replacing cast machine frames by welded frames were chiefly examined. The comparison of welded and cast frames was performed on trimming crank press LDO 500. The core comparison was preceded by analysis of force effects on the frame from the crank mechanism. These effects have been derived from performing operations on this press. Based on the comparison the exact welded and cast frame evaluation was achieved [Cechura, Kucerova and Bouda 2000]. The frame of the press LDO 500 is shown in Figure 10.

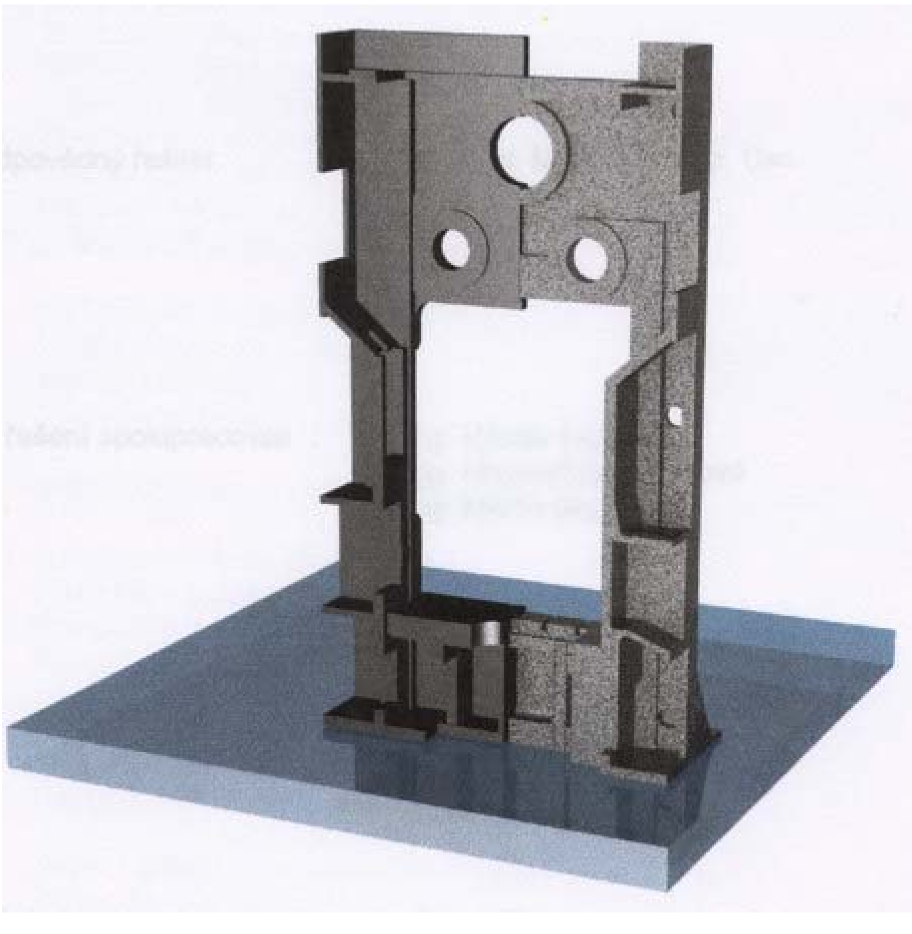


**Figure 10. Frame of press LDO 500**

The analysis of press LDO 500 was followed by the design of large forging crank press LMZ 8000. Force effects were again determined in relation to different kinds of technological operations. Based on this analysis a further solution and possible further paths towards optimization were suggested.

### 3.2 Research and development of vulcanizing presses

Within the framework of the research plan the optimization of the vulcanizing press VL 100V was also carried out. The press VL 100V is shown in Figure 11. It deals with mass optimization of the crossbeam and the pressure vessel of the vulcanizing press. For the crossbeam the optimization was primarily aimed at welded construction and material utilization. For the pressure vessel it dealt with wall thickness and material utilization. The machine housing analysis was also performed by means of Finite Element Method, with focus on the mass decrease and material utilization degree increase.

**Figure 11. Press VL 100V – existing state**

Because the maximum utilization of the current machine construction was guaranteed, a new constructional solution of vulcanizing press VL 100 was designed. Several new design solutions of this press were designed using the application of general rules of material mechanics. For these design solutions one of the criteria was also the possibility of composite material utilization. From these solutions the most suitable design solution has been chosen, shown in Figure 12. This effort has succeeded and at present further research in this area is under way.

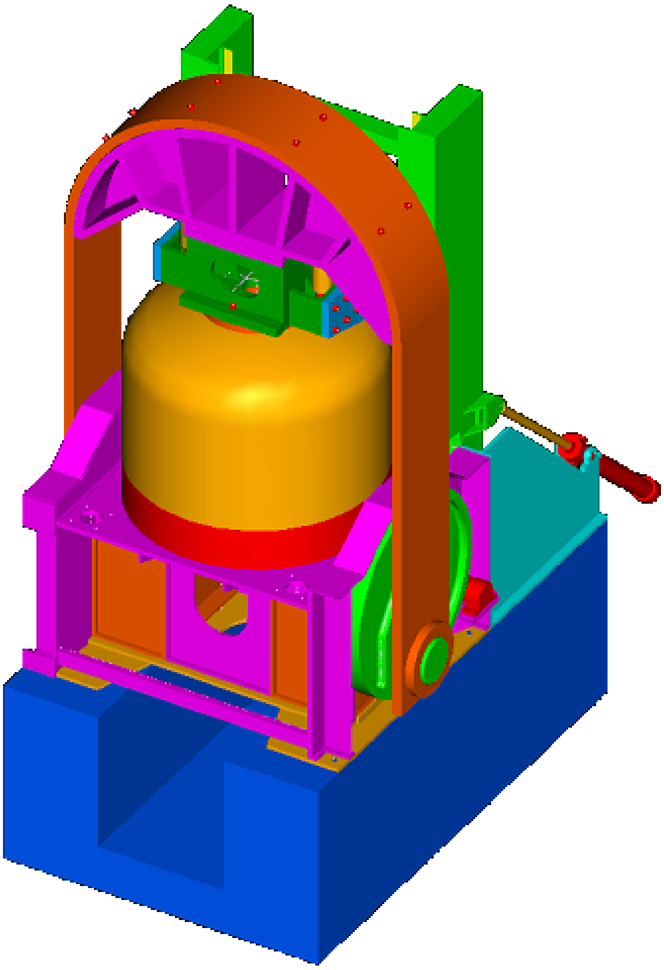


**Figure 12. Press VL 100V – new design solution**

### 3.3 Forming machines – future work

At present the forming machine research team has several sub-tasks. The first task is the detailed analysis of energetic losses in mechanical press operation (screw and crank press). The work sets a goal to determine portions of individual losses depending on used technology, machine design and its energetic balance. From the outcomes of this work a matrix of dependences between used technology, given type of machine and losses will be built up, which will be utilizable in practical application on forming machine design.
Further tasks are the comparison of pre-stressed and un-pre-stressed frame properties. Design of frames which are completely pre-stressed is recently an often-used design modification. Gathering and mutual link-up of sub-items of knowledge is the goal of the work. There is not much time in industry for simulation of individual constructions and load sets by means of modern computational methods (FEM) with the result that it is then a relatively unexplored area and so it is a task for us. Comparison is primarily carried out on frames of hydraulic presses, because in this area of forming machines comparable machines exist.
Further, at present, the explored problem is the influence and propagation of shock waves in hammer foundations. In the area of hammers the forming machine research team is occupied with shock influence upon environment. It is involved in comparison of analytical and numerical computation of hammer foundation by comparison of remnant shock energy transmitted into machine environment. Comparison is carried out on swage hammers (drop and hydraulic), which are most often integrated into the automatic production lines.

## 4. Conclusions

The research on manufacturing machines done within the research plan sub-project has been focused on acquiring new knowledge and methods using systematic approaches of Engineering Design Science based on Theory of Technical Systems, chiefly Theory of Properties based on product lifecycle. These approaches have been applied into individual manufacturing machine areas and the achieved results have contributed to the development of Knowledge Integrated Design Engineering supporting Engineering Design Process in all its phases. The subsequent research plan should be focused on synergic merging of Engineering Design Science-based, material-based and feature-based approaches.


### Acknowledgement

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### References


*Cechura, M., "Comparison of Cast and Welded Frame LDO 500", CTU in Prague, Czech Republic, 2000, ISBN 8023855387.*

*Lasova, V. and Stadler, C., "Numerical Simulation of Mechanical Behaviour of Fibre Wound Tubes", Proceedings of the CO-MAT-TECH 2003, STU Trnava, Slovakia, 2003, ISBN 80-227-1949-8.*

*Navara, V., Stadler, C., Lasova, V. and Kratky, J., "Tool Clamping Device for Machine Tool Spindles", Patent application, University of West Bohemia, Pilsen, Czech Republic, 2002.*

*Novak, P., "Tool clamping device for HSK and its usage", Patent application, University of West Bohemia, Pilsen, Czech Republic, 2003.*

*Sedivy, P., "Unconventional Solution Ways of Frames and Drives of Machine Tool Attachments", Thesis, University of West Bohemia, Pilsen, Czech Republic, 2004.*



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