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AN INVESTIGATION INTO THE APPLICABILITY OF EN24 STEEL FOR SHRINK-FIT TOOL HOLDERS FOR CNC MILLING MACHINES

Summary

This paper investigates the possibility of using an alternative steel material EN 10250 36CrNiMo4/1.6511 (EN24 steel) in the production of shrink-fit tool holders for CNC machining centres. The alternative material has different thermal properties compared to the standard manufacturing material for tool holders (H13 steel), while the mechanical properties are similar. The structural and thermal stress finite element analysis together with the fatigue analysis are performed on a designed model of a tool holder with a shrink-fit clamping head and standard interface for required limiting working conditions. The application of the alternative material combined with the production process optimisation results in reductions in costs and time of producing tool holders, while adhering to all limitations and parameters prescribed by the corresponding standard. Due to higher thermal stresses during tool changes, the usage of an alternative material would be justified for processes where one type of tool is frequently used and the tool lifespan is long.

Key words: *milling machine, shrink-fit tool holder, EN24 steel, finite element analysis*

1. Introduction

In today's industry, the use of numerically controlled machine tools in production processes is widespread [1-5]. The number of numerically controlled machines is increasing daily, along with the demand for spare parts. In addition to making parts, numerically controlled machines are also used to create tools for further production. During the operation of numerically controlled machine tools, it is necessary to perform maintenance to ensure the production continuity and quality of manufactured products. The tool holder is one of the main parts of the machine. Tool holders need to be continuously monitored and replaced as needed [6-8]). Tool damage can occur due to unskilled machine handling, which can result in production errors or possible operator injuries.

This study investigates the applicability of different materials for manufacturing tool holders for numerically controlled machine tools. The research focuses on a particular design of the heat-shrink clamping head SK40, ADB shape, according to the dimensions and maximum stress requirements defined by the ISO 7388-1 standard “Tool shanks with 7/24 taper for automatic tool changers” [9]. The main hypothesis is that by changing the manufacturing material and optimising the processing procedure it is possible to reduce costs and speed up the production process of heat-shrink clamping heads for numerically controlled machine tools.

Alternative steel material EN24 is proposed for the production of shrink-fit tool holders and is compared with the standard steel material used for that purpose (H13 steel). Pressing of the tool into a selected clamping head is performed using an induction device for thermal clamping, hence, the thermodynamic properties of the material chosen for the holder are extremely important.

The goal is to optimise the tool holder production process by reducing the two most important parameters – required production time and cost. The investigation is based on a comparison of the results of the static and dynamic thermal and structural analyses for the standard (H13) and alternative (EN24) steel materials. Structural and thermal stress simulations are performed using the finite element analysis [10] solver AutoDesk NASTRAN integrated into the CAD software AutoDesk Inventor [11].

2. CNC machining centre tool holders

2.1 Standardised designs

For computer-controlled machining centres, tool holder designs are standardised. The most commonly used tool holder designs are CAT, BT, SK, and HSK. CAT is the oldest design, originating in the United States. The improved BT design was developed in Japan. Both designs have a 7:24 taper holder. The SK design was developed in Europe. In the 1990s, Germany developed and introduced the HSK tool holder design, which has a 1:10 taper. In the Eastern European region, the SK and HSK designs are most commonly used [12].

The SK tool holder of the machining centre is shown in Figure 1. The holder is designed so that there is a large clearance between the face of the spindle and the flange of the tool holder. The tapered joint between the tool holder and the spindle has an SK design. This type of connection allows for the self-centring of the cutting tool in the holder, as well as quick and easy clamping and release. Due to its rigidity, the SK design is sensitive to the accuracy of the taper angle of the tool holder and the spindle. The design is sensitive to the axial force applied by the tool.

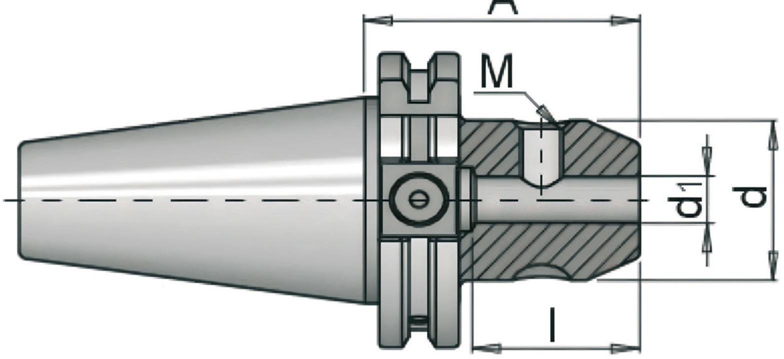


Fig. 1 SK tool holder

The SK design of the tool holder exhibits certain disadvantages when high-precision axial positioning is required. The tool is driven deeper into the spindle by centrifugal forces and drawing forces. The consequences of such tool behaviour are a decrease in the system rigidity, a decrease in the transmitted torque, and a change in the axial position of the tool due to a reduced contact area of the tapered joint. Due to these disadvantages, the SK design of tool holders is rarely used in high-speed machining in the industry.

2.2 Thermal clamping

Methods for the CNC machine centre tool clamping are [12]:

- thermal clamping,
- hydraulic clamping,
- use of a clamping sleeve,
- use of a clamping jaws or a screw.

The most modern method for the cutting tool clamping is thermal clamping [13-15]). This method is based on the expansion of the material, i.e., the proportional increase of the clamping radius due to the heating of the holder. The tool holders are heated to temperatures between 300°C and 340°C. The cutting tool is inserted into the already heated and expanded holder. The tool must be inserted to a precisely defined depth within the holder. As the tool holder cools to room temperature, the tool holder shrinks. This cooling achieves a tight clamping connection between the tool and its holder. Electromagnetic induction is used to heat the tool holders. The machine consists of a coil in which the holder is inserted, generating heat. The heating of the holder takes 5 to 10 seconds, depending on the power of the coil. The heating is localized at the point where the coil of the machine and the holder make contact. Tool holders used for this method of tool pressing are made of special heat-resistant steel. The use of such material allows the tool pressing process to be repeated more than 5,000 times without losing the high elasticity of the material and the centred connection. The joint is mostly cooled by air. The force achieved during clamping is evenly distributed over the entire surface of the joint and is very high. The circularity of the tool rotation with this clamping method is about 0.003 mm.

3. Investigated materials

3.1 H13 steel

Material that is commonly used in the production of shrink-fit tool holders used in the tool changer of a machining centre is the high-temperature steel EN ISO 4957:2000 X40CrMoV5-1, more commonly known as AISI H13 or simply H13. The chemical composition of the H13 steel is shown in Table 1.

H13 tool steel is characterized by good resistance to thermal softening, high hardenability, high strength, and high toughness. This steel is therefore widely used in the production of many different types of hot working moulds, such as forging moulds, extrusion moulds, and die casting moulds. Complex geometries of the product, high material hardness, and short lead times are among the main obstacles to increasing productivity in the machining of such dies [16]. In [17], the difficulty of machining the H13 steel is addressed.

H13 tool steel is a versatile chromium-molybdenum steel used for hot work, widely used in applications for hot and cold work tools due to its high toughness and excellent stability during heat treatment. In these applications, H13 provides better hardenability through hardening in large cross-sectional thicknesses [18]. The ultra-high strength and hardness properties could be achieved by applying heat treatment with quenching and pre-cooling when coming out of the oven to reduce stress concentration and avoid cracking. Table 2 shows properties of the H13 steel used in the analyses, which are achieved with quenching at 1,025 °C and precooling at 995 °C.

Table 1 H13 steel chemical composition

ELEMENTS	PERCENTAGE
Carbon, C	0.32–0.40%
Chromium, Cr	4.75–5.50%
Iron, Fe	>= 90.9%
Molybdenum, Mo	1.33–1.4%
Silicon, Si	1.0%
Vanadium, V	1.0%
Nickel, Ni	0.3%
Copper, Cu	0.25%
Magnesium. Mn	0.20–0.50%
Phosphorus, P	0.03%
Sulphur, S	0.03%

Table 2 H13 steel properties

PHYSICAL PROPERTIES	VALUE AND UNIT	NOTE
Density	7.80 kg/m^3	
Melting point	1,427 °C	
Tensile strength	1,990 MPa	HRC = 55 (hardened at 995–1,025 °C)
Yield strength	1,650 MPa	HRC = 55 (hardened at 995–1,025 °C)
Elongation at break	9.0 %	HRC = 55 (hardened at 995–1,025 °C)
Elastic modulus	210 GPa	
Compressive modulus	160 GPa	
Poisson's ratio	0.30	Calculated
Machinability	50 %	
Shear modulus	81.0 GPa	
Specific heat capacity	460 J/(kgK)	For temperature range 0–100 °C
Thermal conductivity	24.3 W/(mK)	At temperature 215 °C
Coefficient of thermal expansion	12.2 µm/(mK)	For temperature range 20–425 °C

3.2 EN24 steel

EN 10250 36CrNiMo4/1.6511 steel, better known as EN24, was selected as an alternative material. In most work environments EN24 is equivalent to the AISI 4340 steel. EN24 steel is a medium carbon, low alloy steel known for its toughness and strength in generally large sections. EN24 is also a type of nickel-chromium-molybdenum steel. It can be delivered hardened and tempered in the tensile range from 930 to 1,080 MPa as well as annealed. Previously quenched and tempered EN24 steels can be further surface hardened by flame or induction hardening and nitriding. When it first became widespread in the early 1900s, EN24 was classified as a forged steel for automobiles and aircraft, and as such, it was used to produce numerous parts and components for these industries [19]. It is most popular as EN24T and, with good high tensile properties in the T condition, it is widely used in the manufacturing sector. The chemical composition of the steel is shown in Table 3.

Heat-treated EN24 offers high tensile strength combined with good ductility and impact resistance. Good impact values can be achieved at low temperatures. The chosen alternative material is similar in its characteristics to the material commonly used for making CNC machine tool holders, but the possibility of production according to the standard requirements needs to be analysed. The properties of ultra-high strength and hardness could be achieved by quenching and tempering [18]. Table 4 shows the properties of the EN24 steel used in the analyses, which are achieved by applying oil quenching from 845 °C and tempering at 200 °C.

Table 3 EN24 steel chemical composition

ELEMENTS	PERCENTAGE
Carbon, C	0.38–0.43%
Chromium, Cr	0.70–0.90%
Iron, Fe	95.6–97.2%
Molybdenum, Mo	0.15–0.30 %
Silicon, Si	0.20–0.30%
Vanadium, V	–
Nickel, Ni	1.65–2.00%
Copper, Cu	0.25%
Magnesium. Mn	0.50–0.80%
Phosphorus, P	<= 0.035%
Sulphur, S	<= 0.04%

Table 4 EN24 steel properties

PHYSICAL PROPERTIES	VALUE AND UNIT	NOTE
Density	7.80 kg/m^3	
Melting point	1,370–1,400 °C	
Tensile strength	1,900 MPa	HRC = 53 (normalized at 200 °C)
Yield strength	1,550 MPa	HRC = 53 (normalized at 200 °C)
Elongation at break	12.0 %	HRC = 53 (normalized at 200 °C)
Elastic modulus	210 GPa	
Compressive modulus	80 GPa	
Poisson's ratio	0.29	Calculated
Machinability	57 %	
Shear modulus	73 GPa	
Specific heat capacity	477 J/(kgK)	For temperature range 50–100 °C
Thermal conductivity	42.7 W/(mK)	At temperature 100 °C
Coefficient of thermal expansion	13.7 µm/(mK)	For temperature range 20–400 °C

4. Shrink-fit tool holder model and finite element analysis

A shrink-fit tool holder SK40 model, a finite element mesh and simulations are made with the integrated CAD simulation software tool AutoDesk Inventor Nastran [11]. The model meshing and final mesh acceptance were performed through a two-stage procedure, with each stage containing a mesh sensitivity analysis for three different mesh sizes. The first meshing stage was based on the automatic mesh refinement performed with the AutoDesk Inventor Nastran software defined by the fraction of the minimum element size and the global element size set to 0.2. Three different mesh sizes specified with global element sizes of 5, 3 and 1.5 mm were analysed. The maximum von Mises equivalent static stress resulting from the static stress simulations for the alternative EN24 material is used as criterion for the mesh sensitivity study and the results are presented in Table 5. The model geometry and the finite element mesh with 3 mm global element size are shown in Figure 2.

Table 5 Mesh sensitivity analysis with automatic mesh refinement

Global element size /mm	Nodes	Elements	Max. von Mises stress /MPa
5	43,061	27,877	28.89
3	139,196	94,526	29.99
1.5	981,978	710,673	29.09

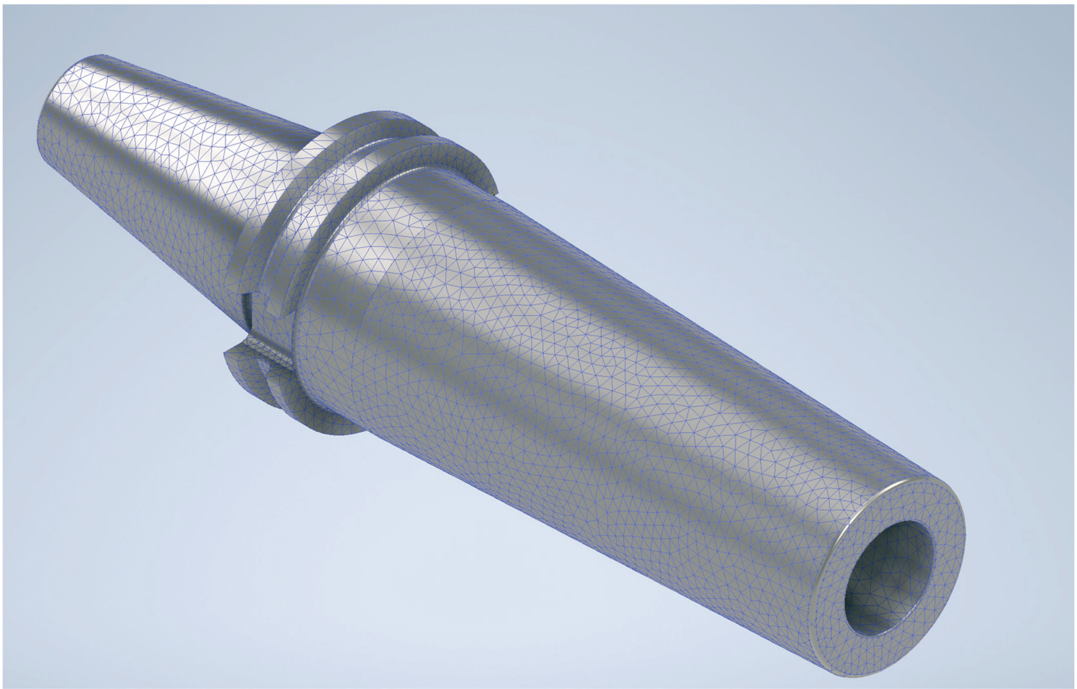


Fig. 2 SK40 tool holder model and finite element mesh

With the presented meshing approach, the static stress simulations of the alternative EN24 material showed that the maximum von Mises equivalent static stress occurs at the transition zone between the cylindrical and the conical geometry for all mesh sizes. According to that finding and the requirement to refine the mesh in the middle area of the fork holder gripping system geometry, a new improved local mesh refinement was performed in those areas, with the local refinement element size defined as 0.33 fraction of the corresponding global element size. These results of the stage two of the mesh sensitivity study are presented in Table 6.

Table 6 Mesh sensitivity analysis with improved local mesh refinement

Global element size /Local refinement element size /mm	Nodes	Elements	Max. von Mises stress /MPa
5 / 1.67	60,716	38,888	32.45
3 / 1	191,669	128,553	34.07
1.5 / 0.5	1,299,978	710,673	33.95

The 3 mm mesh gave the highest maximum von Mises equivalent stress with a very small difference from the maximum stress of the finer 1.5 mm mesh. The optimal simulation time efficiency and negligible difference in the mesh sensitivity criterion were the reasons to accept the 3mm mesh with local refinement as a satisfactory mesh for further analyses. The final accepted mesh is shown in Figure 3, while the corresponding mesh refinement details are shown in Figure 4.

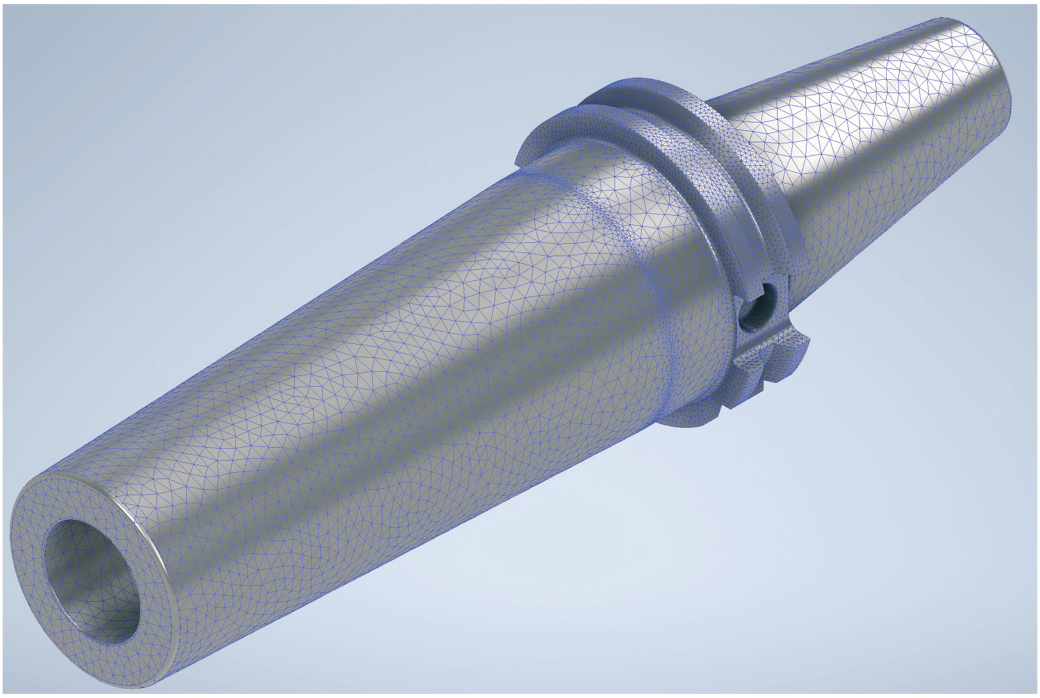


Fig. 3 Selected 3 mm finite element mesh with local refinement

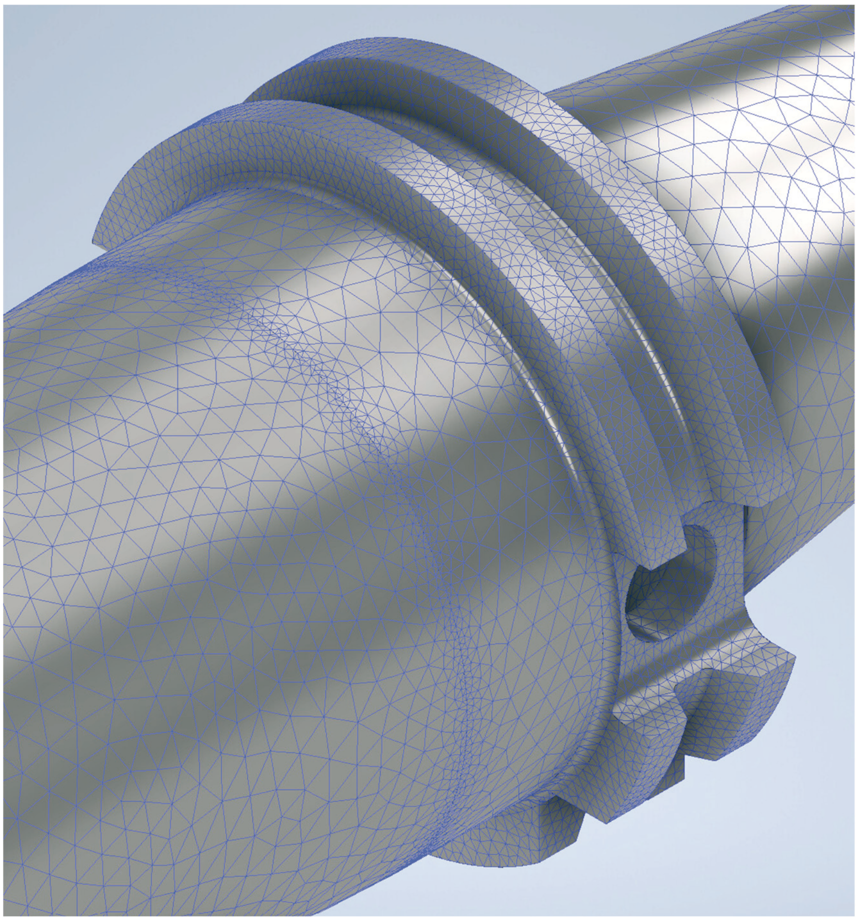


Fig. 4 Local mesh refinement detail

The same tool holder model was subjected to the static load analysis, fatigue analysis and thermal stress analysis and the results were compared for both steel materials, H13 and EN24. The analyses were based on the standard requirement [9] that each tool holder must be designed to perform at least 5,000 cycles without fatigue and loss of concentricity. The designed tool holder is used in the production of large quantities, in high-precision machining, at high spindle speeds, and with large spindle displacements. For the specified application, machine tools with less powerful spindle slopes have the possibility of rotation at a high number of revolutions. The following requirements are prescribed for the designed tool holder:

- maximum torque moment load of 200 Nm on the tool holder without exceeding the material yield strength
- no cone deformation outside the tolerances prescribed by the standard and the circularity of the tool holder according to the manufacturer's specifications, i.e. 0.003 mm.
- tool holder service life of at least 400 working hours
- at least 5,000 cycles of thermal tool exchange in the holder without tool holder cracking.

The static load analysis was based on standard limitations set on maximum allowable uniaxial and equivalent stresses and displacements. The von Mises yield criterion was used for the equivalent stresses and displacements checks [20].

For the fatigue analysis, a cyclic load was defined, modelled as a typical cycle of using a CNC machine tool during material processing. S-N curve parameters for both materials were obtained from the research results published in [18] and [21].

The nonlinear thermal analysis [22, 23] was performed in such a way that the time required to heat the cone holder was analysed. It is necessary to achieve a contact surface temperature of the holder and tool in the range from 300 to 340 °C and then to cool the entire model to room temperature of 24 °C.

5. Results

5.1 Static load analysis

The results of the static load analysis for both materials are compared and shown in Table 7. The resulting contours of the von Mises equivalent stress and displacement corresponding to the maximum torque moment load of 200 Nm for the EN24 steel are shown in Figures 5, 6 and 7.

The results are similar for both steel materials due to their similar mechanical characteristics. For the standard material H13, the maximum stress according to the von Mises theory is 34.11 MPa, while for the alternative material EN24, it is 34.07 MPa. The alternative material shows a slightly larger maximum equivalent displacement of 0.005449 mm, and for the standard material, it is 0.004984 mm.

For the tool holder model simulations with both materials, the maximum von Mises equivalent static stress occurs in the transition zone between the cylindrical and the conical geometry . The maximum stress zone does not have radial symmetry due to the influence of the middle area of the fork holder gripping system, in the middle of the holder, that is not radially symmetrical. Figure 6 shows the maximum stress zone from the opposite side of the holder.

The inner wall of the holder meets the standard accuracy of a maximum of 0.003 mm displacement. Under the maximum load condition, the analysis recorded maximum displacements at the inner wall of 0.002432 mm in the case of the standard material and 0.002670 mm in the case of the alternative material. The results obtained from the stress and deflection analysis in all axes and planes show negligible differences between the alternative and the standard material due to minor differences in their mechanical properties.

Table 7 Results of static load simulations (H13 and EN24)

	H13 (X40CrMoV5-1)	EN24 (36CrNiMo4/1.6511)
Von Mises equivalent stress /MPa		
Maximum	34.11	34.07
Minimum	0	0
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Equivalent displacement /mm		
Maximum	0.004984	0.005449
Maximum at inner wall	0.002432	0.002670
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Stress X-axis /MPa		
Maximum	18.49	18.18
Minimum	-18.81	-18.52
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Stress Y-axis /MPa		
Maximum	35.59	35.32
Minimum	-34.83	-34.71
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Stress Z-axis /MPa		
Maximum	11.83	11.34
Minimum	-11.67	-11.36
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Stress XY-plane /MPa		
Maximum	7.95	7.98
Minimum	-13.98	-13.95
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Stress XZ-plane /MPa		
Maximum	12.63	12.60
Minimum	-8.45	-8.44
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Stress YZ-plane /MPa		
Maximum	8.30	8.28
Minimum	-8.11	-8.12
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Displacement X-axis /mm		
Maximum	2.574×10^{-04}	2.859×10^{-04}
Maximum at inner wall	1.310×10^{-05}	1.449×10^{-05}
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Displacement Y-axis /mm		
Maximum	0.004939	0.005417
Maximum at inner wall	0.002432	0.002665
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*
Displacement Z-axis /mm		
Maximum	0,004826	0,005294
Maximum at inner wall	0,000151	0,000166
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*

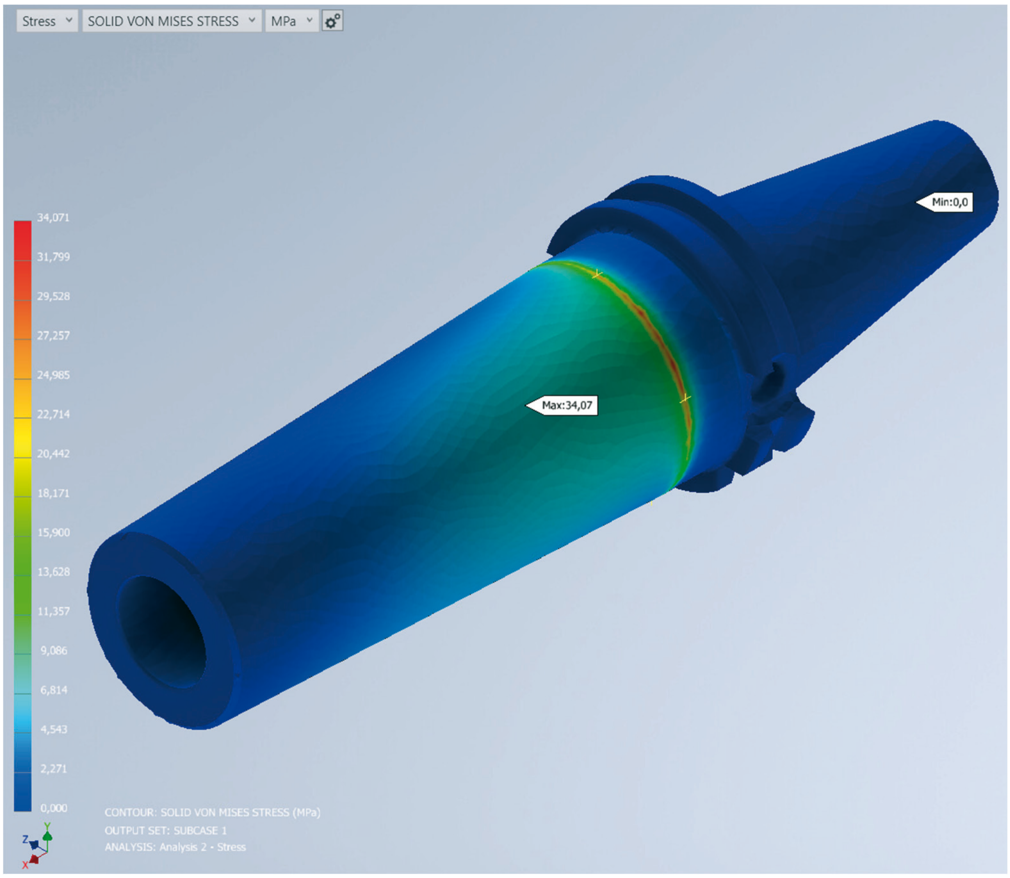


Fig. 5 EN24 von Mises equivalent stress for maximum static load

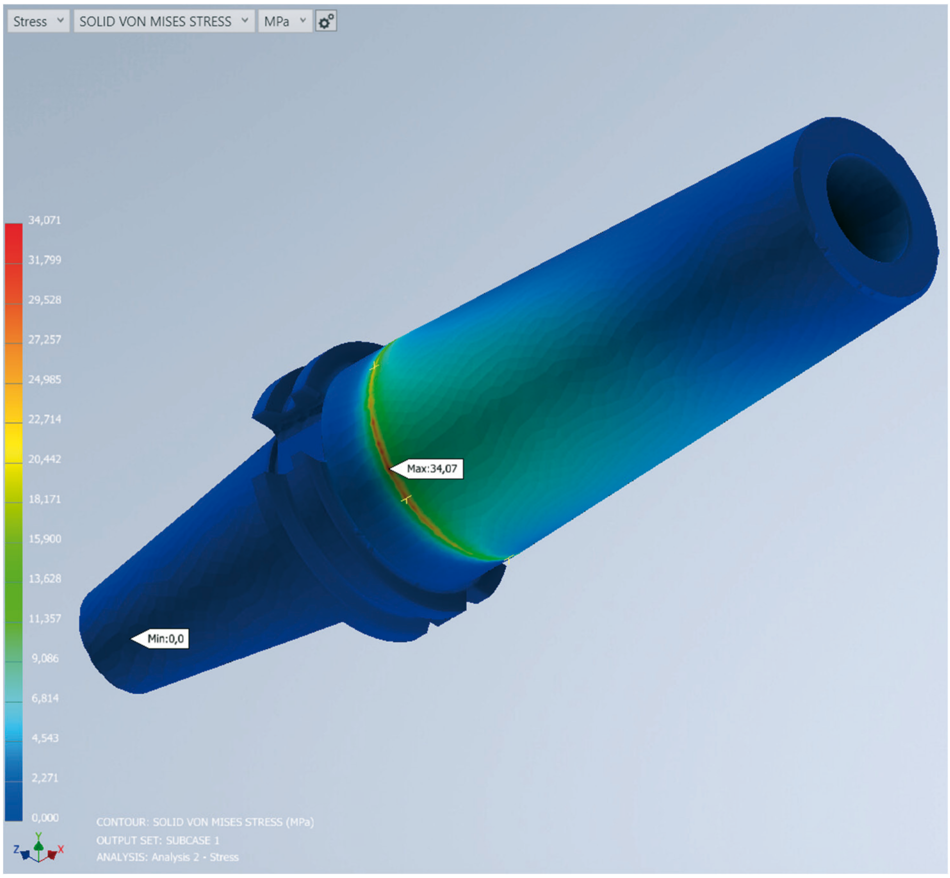


Fig. 6 EN24 von Mises equivalent stress for maximum static load, opposite side view

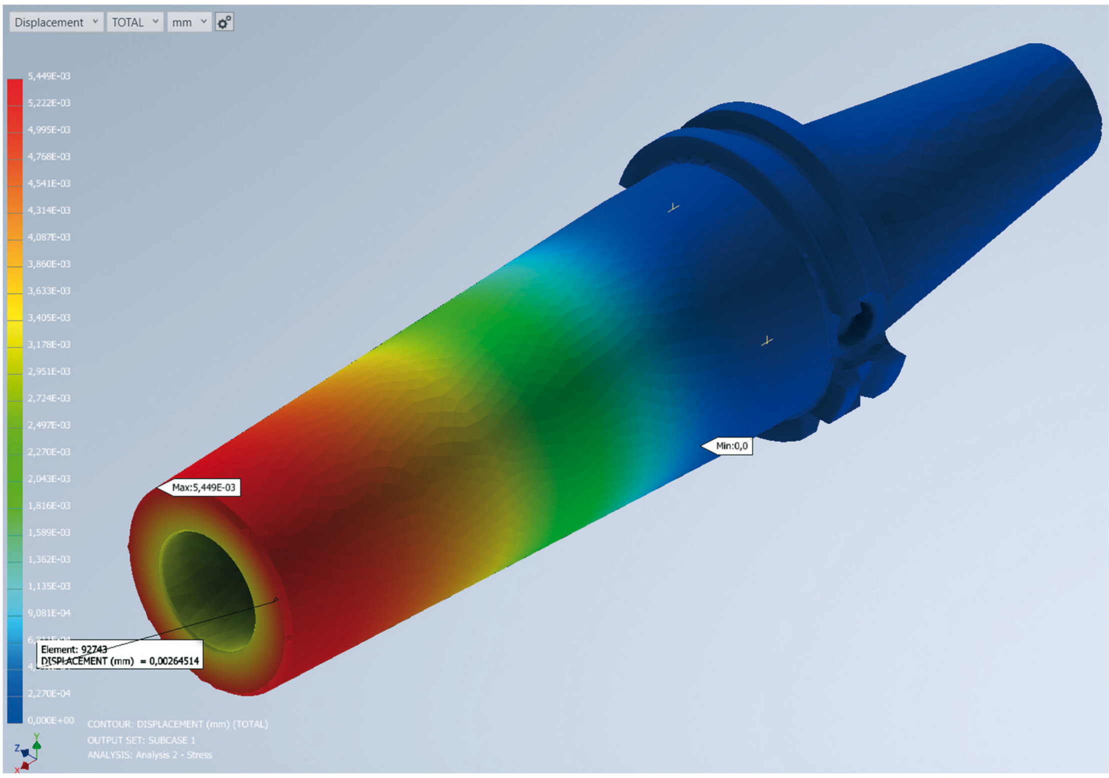


Fig. 7 EN24 equivalent displacement for maximum static load

5.2 Fatigue analysis

During one cycle under the maximum stress, both materials meet the allowable tolerances of the cone mating and the allowable roundness of the tool holder. It is necessary to examine the behaviour when increasing the number of load cycles.

The results of the fatigue analysis for the cyclic maximum load, defined as one processing cycle where the load lasts for the longer part of the cycle, show that both materials meet the required condition. The results are shown and compared in Table 8 and the results of contours of fatigue life for the EN24 steel are shown in Figure 8. Due to the simulation software limit on the number of stress cycles of 10^{10} the fatigue life results are uniform across the whole domain and equal to the limit number. Small result fluctuations observed in Figure 8 are a consequence of the simulation numerical fluctuations. This proves that the tool holder lifespan is more than 10^{10} repetitions under ideal conditions. With an average duration of one load cycle, the tool holder lifespan is more than 400 working hours, which meets the defined requirements.

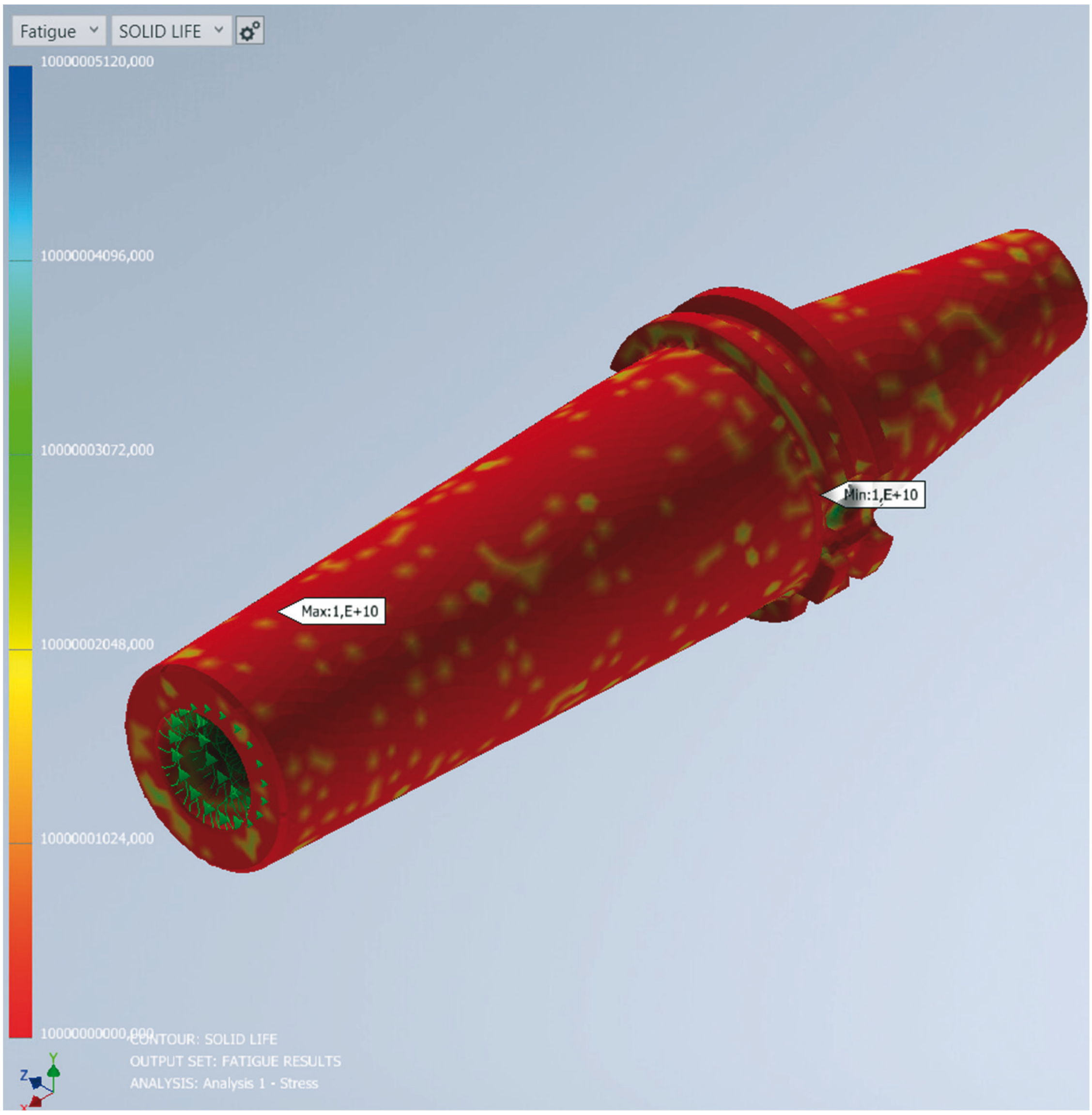


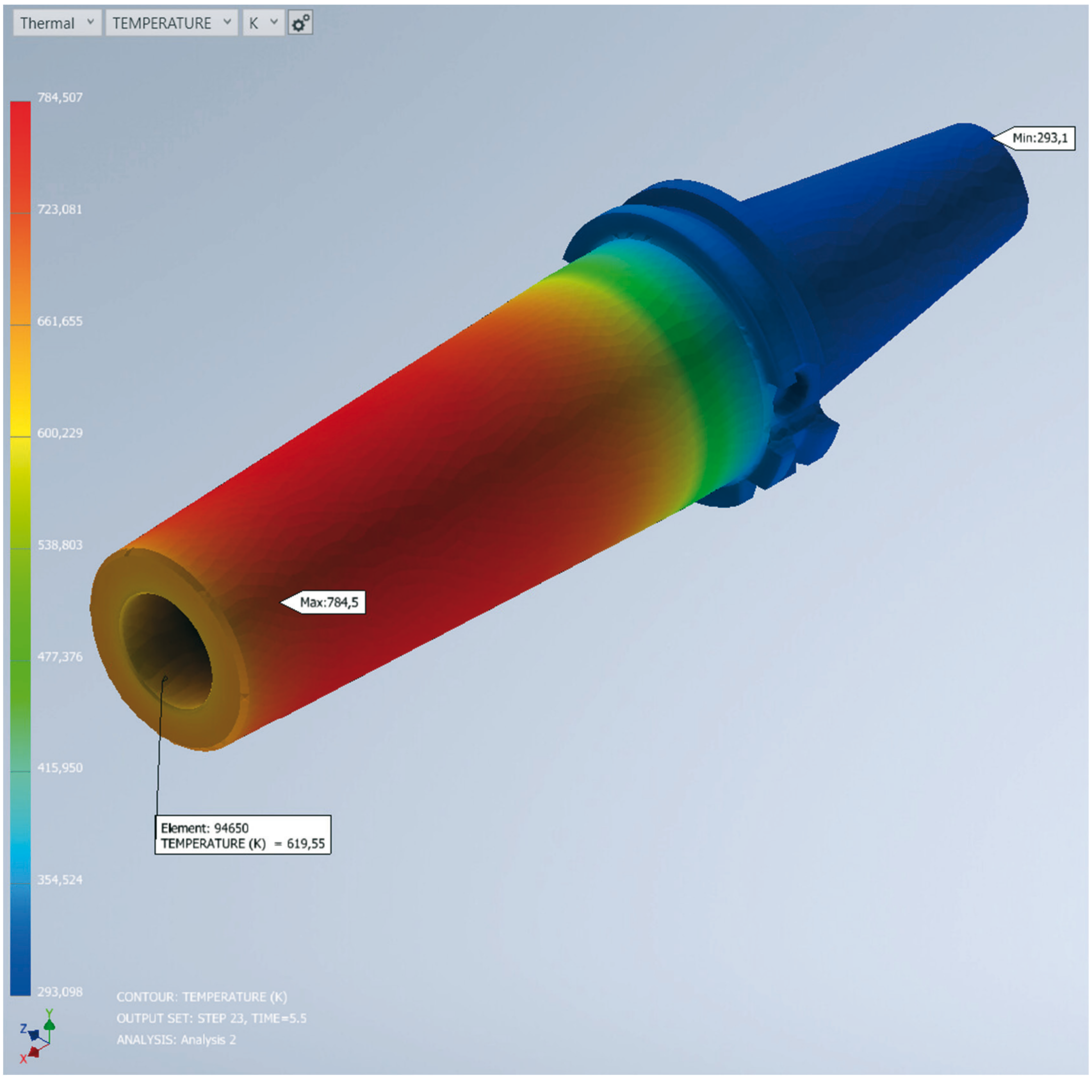
Fig. 8 EN24 steel material fatigue life

Table 8 Fatigue analysis results (H13 and EN24)

	H13 (X40CrMoV5-1)	EN24 (36CrNiMo4/1.6511)
Minimum number of cycles before failure	1×10^{10}	1×10^{10}
Average working hours before failure /h	400+	400+
Meeting conditions	*Conditions satisfied*	*Conditions satisfied*

5.3 Thermal stress analysis

Significant differences between the used materials were observed in the thermal analysis, with summary results shown in Table 9. The power of the standard industrial induction heating machine was defined as the load. In the case of the standard material model, it took three seconds to heat the inner surfaces to a temperature range suitable for tool insertion, while it took 5.5 seconds in the case of the alternative material. When the inner surface temperature was at the upper limit of the range, i.e. around 615 K, the outer surface temperature of the model made from the standard material was 763.7 K, while in the case of the alternative material, it was 784.5 K. The higher surface temperature is a result of the higher thermal conductivity and slightly higher specific heat capacity of the alternative material.



Element: 94650
TEMPERATURE (K) = 619,55

CONTOUR: TEMPERATURE (K)
OUTPUT SET: STEP 23, TIME=5.5
ANALYSIS: Analysis 2

Fig. 9 EN24 temperature distribution

After a 60-second cooling cycle, both models reached the room temperature approximately. During the analysis of static load during the period of the highest temperature, the maximum stress in the alternative material was significantly higher. That is due to different thermal properties. EN24 has higher thermal conductivity and thermal expansion coefficients.

The maximum stress according to the von Mises theory in the case of the standard material is 283.7 MPa, while in the case of the alternative material, it is 535.3 MPa. This maximum stress affects the tool holder made from the alternative material, resulting in a drastically reduced number of tool change cycles. However, it still meets the set conditions of at least 5,000 changes.

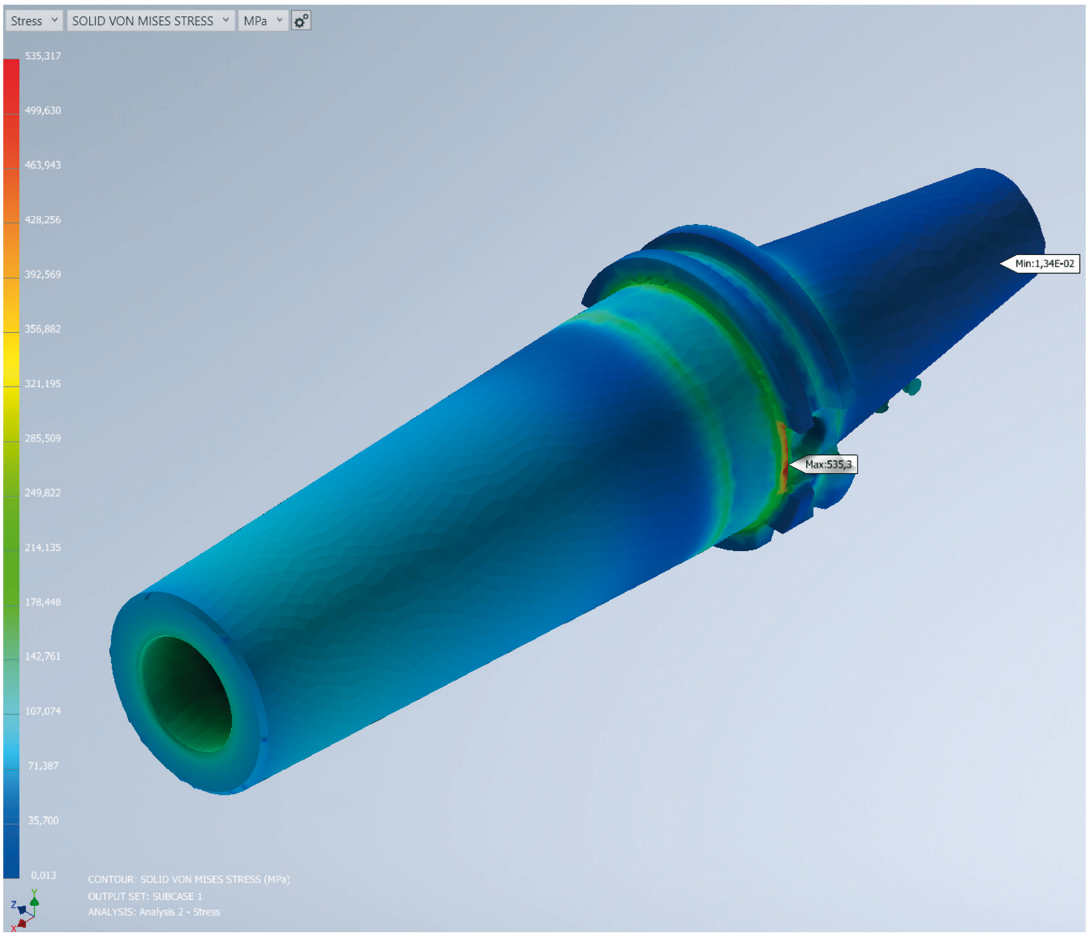


Fig. 10 EN24 von Mises equivalent thermal stress

Table 9 Thermal stress analysis results (H13 and EN24)

	H13 (X40CrMoV5-1)	EN24 (36CrNiMo4/1.6511)
Heating		
Time /s	3	5.5
Highest temperature /K	763.4	784.5
Holder temperature /K	617.4	619.3
Cooling		
Time /s	60	60
Highest temperature /K	308.8	316.0
Holder temperature /K	305.7	303.1
Von Mises equivalent stress /MPa		
Maximum	283.7	535.3
Stress condition	*Condition satisfied*	*Condition satisfied*
Equivalent displacement /mm		
Maximum	0.5096	0.6721
Minimum	0	0

6. Conclusion

This paper investigates the possibility of using EN 10250 36CrNiMo4/1.6511 steel (EN24) in the production of a tool holder with a heat-shrink clamping head based on the ISO SK40 reception. The investigation is based is on a detailed finite element analysis of the model of a tool holder with a shrink-fit clamping head and an SK standard interface according to the dimensions and design requirements of the ISO 7388-1 standard [9].

The static load analysis, the fatigue analysis and the thermal stress analysis of the developed model are conducted with the integrated CAD simulation software tool AutoDesk Inventor Nastran [11]. The analyses were performed on the same model using the H13 steel, which is a standard manufacturing material, and the EN24 steel, which was selected as an alternative material. The chosen alternative material has similar mechanical properties to the standard material for manufacturing tool holders, while their thermal properties differ. The stress analyses were conducted at the maximum stress of 200 Nm, which is the maximum power the machining spindle can deliver. The parameters that the tool holder manufactured from the selected material must meet are that the maximum load of 200 Nm can be applied on the tool interface and the cone without deformations beyond the tolerances prescribed by the standard and manufacturer's specifications and that it can withstand at least 5,000 cycles of thermal tool exchange in the holder without cracking. The static load structural analysis showed that the alternative material meets the set criteria. The maximum stress is the same in both models, while the equivalent displacement is slightly higher in the case of the alternative material. The tool holder service life meets the requirements, as determined by the fatigue analysis. During tool changes, the model constructed with the alternative material requires longer heating, and the stresses during the change are significantly higher than with the standard material.

The obtained simulation results lead to a conclusion that it would be feasible to use the EN24 steel in the production of tool holders. Its drawback, which was observed in the reduced number of tool change cycles, can be compensated by using such a tool holder in applications where frequent tool changes are not required. It is also necessary to highlight the inferiority of the chosen alternative material observed during thermal loading during tool changes. The use of such a designed tool holder would be suitable in processes where one type of tool is frequently used and the tool lifespan is long. Further prototype experiments and tests are required for the verification of the simulation results and conclusions.

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