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MATERIALS AND TECHNOLOGIES IN THE DESIGN OF MILITARY OPTICAL DEVICES

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Abstract: Modern technologies offer promising possibilities in the design of optical devices through the use of advanced materials. These materials enable modifications of certain parameters, such as size, weight, and imaging properties, while also reducing costs by utilizing more affordable materials and lower-cost production methods. This article provides an analysis of the properties required to ensure the desired imaging quality, along with an overview of current and prospective modern materials suitable for constructing the bodies of optical devices.

Keywords: Design; Optical device; Invar; Aluminum; Polyethylene; Imaging errors; Temperature effects.

1 INTRODUCTION

Optical devices are designed to convert information from the observation (detection), measurement, or control of an object.

The fundamental components of optical instruments, including aiming telescopes, are all the parts that the designer must consider and that affect its properties. The basic building blocks include:

a) Imaging elements – these create an image of the objects in the desired position, size, and quality.

b) Auxiliary elements – these affect the position or orientation of the image but do not have a direct impact on its parameters. The optical tube of the instrument is classified as an auxiliary element. From this characterization, it might seem like a less important part of the device, but the opposite is true. In fact, the tube and all parts responsible for ensuring the correct positioning of the imaging elements have a significant impact on image quality.

Among the basic requirements we can include:

- **Sufficient strength and material durability –** the tube of a targeting telescope must ensure the stability of the optical elements' position even under shocks caused by recoil from a shot or during rough handling in combat operations.
- **Minimal thermal expansion –** ensure the correct positioning of the optical elements (objective lens, collector lens, reversing system, focal plate, and eyepiece) even with changes in the ambient temperature in which the optical instrument is used.

In the construction of a targeting telescope, the quality of the image is influenced by the appropriate selection of structural components of the telescope body, focal lengths, and the precision of mounting the optical parts, such as the objective lens, reversing system, and eyepiece [1].

The accuracy of aiming with a telescope will be influenced not only by the aforementioned construction parameters but also by changes in temperature and atmospheric turbulence. Temperature, as an external factor, affects the size of the optical system. This leads to thermal expansion of the dimensions of the structural components as well as thermal optical aberrations of the objective lens. This can be mitigated in the design of the telescope through careful selection of materials and the structural arrangement of the optical system. It is essential to ensure that the construction materials have minimal sensitivity to temperature changes and that these thermal variations are mutually compensated [1].

Atmospheric turbulence causes changes in the angles of incidence of rays on the entrance pupil of the telescope's objective lens $\boldsymbol{\Delta\beta}$. This disrupts the relationships between various parameters in the construction of optical elements. However, these effects cannot be completely eliminated by technical means [1].

2 ERRORS IN THE IMAGE OF AN OPTICAL SIGHT DUE TO TEMPERATURE AND ITS VARIATIONS

With changes in temperature of the telescope's structural components, there will be a change in their dimensions. If we assume that the temperature change affects only the length of the telescope body and does not impact the optical axis [1].

The deviation in the power of the telescope caused by changes in individual parameters is given by the relationship:

$$dK = \sqrt{\left(\frac{\partial K}{\partial \rho}\right)^2 . \Delta\rho^2 + \left(\frac{\partial K}{\partial f'}\right)^2 . \Delta f'^2} \tag{1}$$

where $\boldsymbol{K}$ is the magnification of the telescope, $\boldsymbol{\rho}$ is the resolving power of the device, and $\boldsymbol{f'}$ he focal length of the objective lens.

After adjustment, we obtain the relationship for the deviation in the structural dimensions of the body and the focal lengths of the objective lens:

$$dK = K.\sqrt{\frac{\Delta \acute{f}^2}{\acute{f}^4}} \qquad (2)$$

If we vary the temperature of the sight body within the range $\boldsymbol{t \in \langle -20 \div 40 \rangle °C}$ and the coefficient of expansion $\boldsymbol{\alpha = 15 \cdot 10^{-6}\, m \cdot °C^{-1}}$. I will address this change in characteristics, which is significantly more complex, in the following text [1].

2.1 Thermo-optic aberrations of the objective lens and the position of the objective lens

A change in the temperature of the telescope will cause, in addition to structural changes in the body (tube) and optical system, alterations in the characteristics of image quality. These changes will be referred to as thermal aberrations in the following text [1].

Thermo-optic aberration of the image position is conditioned by:

- the dependence of the refractive index of the lenses on temperature,
- the change in the radius of curvature of the lens surfaces and the change in their thickness with temperature variations,
- the change in the distances between the lenses, which results from the thermal expansion of the telescope body material and the lens mounts [1].

In addressing thermo-optic aberrations and their impact on image quality, I will work with steady states. This means that the entire system is at the same temperature at the time of measurement [1].

If we consider that the coefficient of linear expansion of glass is temperature-dependent, it can be assumed that within certain precisely defined temperature change intervals, we can work with its average value. To correct the monochromatic aberration of the objective lens, we need to have a precisely defined wavelength of light for which we will analyze the aberration, as the thermal increment in the refractive index of light $\boldsymbol{\frac{dn}{dt}}$ is dependent on this wavelength $\boldsymbol{\lambda}$ [1].

In designing an optical system that does not misalign with temperature changes, this can be achieved by selecting special types of materials for the lenses, lens mounts, and the body, to prevent changes in focal lengths and the occurrence of optical aberrations [1].

For an optical system consisting of optical surfaces, the optical aberration of the image position due to a change in temperature is given by the relationship:

$$d\acute{s}_k = \frac{n_1.h_1^2.\acute{s}_k^2}{\acute{n}_k.h_k^2.s_1^2}.ds_1 - \frac{h_1^2.\acute{s}_k^2}{\acute{n}_k.h_k^2}.T_1 \qquad (3)$$

where $\boldsymbol{s'}$ is the image position [m], $\boldsymbol{h}$ is the distance from the target to the objective lens [m], $\boldsymbol{n}$ is the number of refracting surfaces, and $\boldsymbol{T_1}$ is the coefficient of thermo-optic aberration of the image position. The relationship for this coefficient is given by:

$$T_1 = \sum_{i=1}^{k} \frac{h_i^2}{h_1^2}.\left[Q_{s,i}.\left(\frac{d\acute{n}_i}{\acute{n}_i} - \frac{dn_i}{n_i}\right).(\acute{n}_i - n_i).\frac{dr_i}{r_i^2}\right] + \sum_{i=2}^{k} \frac{h_i^2}{h_1^2}.\frac{n_i}{s_i^2}.dd_{i-1} \qquad (4)$$

where $\boldsymbol{Q_s}$ is the zero invariant of the ray's refractive index on the surface:

$$Q_s = n.\left(\frac{1}{r} - \frac{1}{s}\right) = \acute{n}.\left(\frac{1}{r} - \frac{1}{\acute{s}}\right) \qquad (5)$$

where $\boldsymbol{r}$ is the radius of the entrance pupil of the sight [m].

3 SELECTION OF MATERIAL FOR THE BODY OF A TARGETING TELESCOPE

In optical instruments, the material of the body and its properties are considered somewhat differently compared to mechanical engineering. Various materials with different properties, in terms of construction and processing methods, can be used. The emphasis is not primarily on the material's strength but rather on its machinability, dimensional stability, and shape stability.

All materials experience plastic deformation due to stress and especially due to heat. This is caused by flow and molecular instability of the material.

In mechanical engineering, flow is most commonly observed in components subjected to high temperatures, which occurs very infrequently in precision mechanics and optics. The manifestation of flow varies among materials. For example, it is minimal in fused quartz, while it is significant in zinc.

Internal stresses in a material arise either directly within the material itself or due to external influences. These stresses can occur during processes such as hardening. Annealing relieves these stresses, but not completely. Subsequently, flow may begin to manifest, and the component can continue to change its dimensions for years. For materials like duralumin, which is not annealed after thermal processing, these dimensional changes are significantly greater compared to steels.

Internal stresses also develop during cold processing, such as rolling and cold drawing. For example, in the drawing of a rod, the surface layer may experience compressive stresses, while tensile stresses occur inside the rod to maintain equilibrium. Reducing the diameter of the rod during machining removes some of the compressive stress [2].

Figure 1a shows that if a rod is machined symmetrically and the stress is also distributed symmetrically, the internal stress remains uniformly distributed. The tensile stress inside the rod decreases, while the compressive stress on the surface increases,resulting in a shortening of the rod. Figure 1b and Figure 1c illustrate the asymmetric distribution of stresses in the case of asymmetric machining and, conversely, symmetric machining if the stress distribution was asymmetric [2].

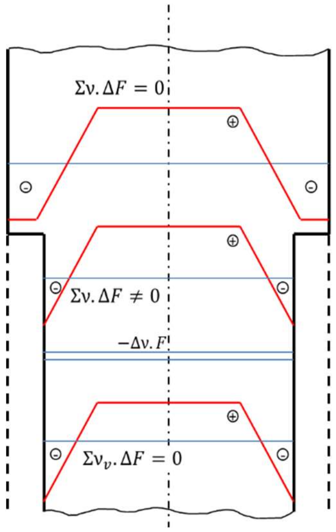

Fig. 1a Symmetrical distribution of internal stresses and symmetrical machining Source: [2].

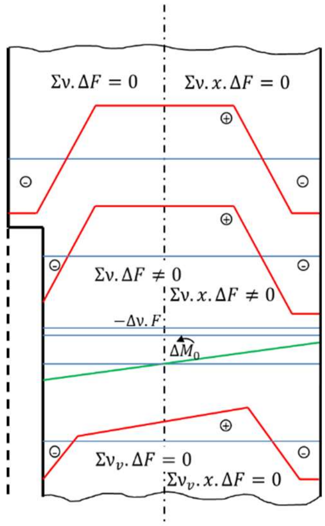

Fig. 1b Symmetrical distribution of internal stresses and asymmetric machining Source: [2].

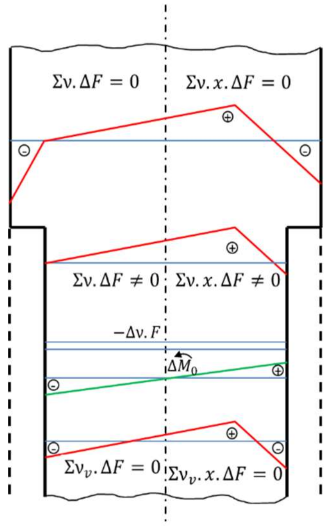

Fig. 1c Asymmetrical distribution of internal stresses and symmetrical machining Source: [2].

Dimensional and shape changes can be caused by molecular instability of the material, which may manifest spontaneously over the long term.

In precision mechanics and optics, the change in length due to temperature is also of significant importance. It can be approximately expressed by the equation:

$$\Delta L = L.\alpha.\Theta \quad [mm] \tag{6}$$

where: $\boldsymbol{L}$ is the original length in mm;
$\boldsymbol{\alpha}$ is the coefficient of thermal expansion;
$\boldsymbol{\Theta = (t_1 - t_2)}$ is the temperature difference in °C.

The cause of a material's thermal properties is the thermal vibrations of atoms. At absolute zero ($0K = -273{,}15°C$), the atoms are in a stable position, and the atomic lattice has a zero equilibrium value. As the temperature increases, the atoms vibrate more and more, and at constant pressure, they move farther apart, which subsequently manifests as thermal expansion. This refers to the volumetric change $\boldsymbol{V}$ caused by an increase in temperature $\boldsymbol{T}$ at constant pressure $\boldsymbol{p}$ [2].

It can be expressed by the relationship:

$$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P \tag{7}$$

For selecting materials for the body of a targeting telescope, I will focus on two commonly used materials in optics and one modern material. I will compare these materials in terms of their response to temperature changes [3].

3.1 Invar

Invar (from the French "invariability") is an alloy of iron with 36 % nickel. It has the lowest thermal expansion among metals. It is silver-gray, corrosion-resistant, and a very poor conductor of heat and electricity. The coefficient of thermal expansion depends on the alloying elements, impurities, and both thermal and mechanical processing. There are several variants of Invar with coefficients of thermal expansion of 0.8, 1.0, 1.6, and $2{,}5.10^{-6}$. The instability of this material is manifested in temporal irregularity and thermal expansion, especially in slowly occurring length changes, which can appear over years. Complex long-term artificial aging processes do not help either. One method of stabilization is to place the Invar rod into a thin, long solenoid connected to the power supply for 48 hours, where the alternating current excites the molecules through alternating magnetization, causing alternating longitudinal changes due to magnetostriction (changes in material dimensions when magnetized), and also because the rod slightly heats up. More modern types of Invar, which are slightly alloyed with additional elements such as chromium, show more regular behavior. Adding cobalt as an alloying element can reduce the coefficient of thermal expansion of Invar at low temperatures (up to 100°C). This alloy is called Superinvar [2, 4].

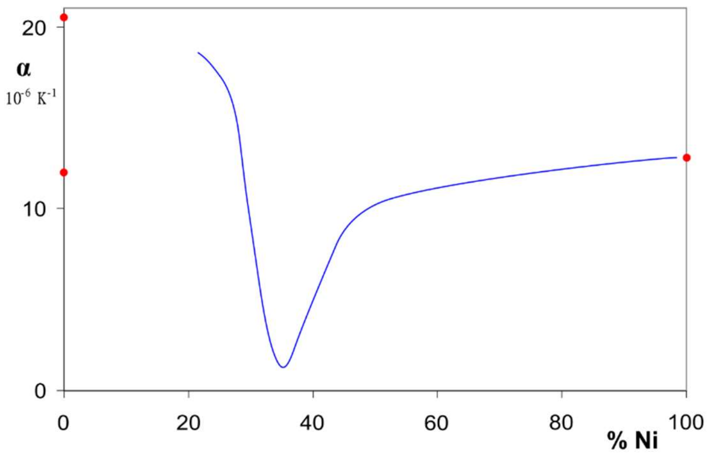

Fig. 2 The effect of nickel on changes in the coefficient of thermal expansion
Source: [5].

Tab. 1 Basic Properties of alloy FeNi36 – Invar

Density at 20°C	8100 kg./m^3
Melting temperature	1450°C
Coefficient of expansion at 20°C and 100°C	1,2 10^{-6} K^{-1}
Hardness (HB)	220
Modulus of elasticity at 20°C	140 GPa
Yield strength	700 MPa
Tensile strength	750 MPa

Source: [6].

Applications of Invar:

Invar is used for applications requiring the lowest possible thermal expansion.

Most common uses [7]:

- Manufacturing, storage, and transportation of liquefied gases;
- Components for OLED displays;
- Measurement and control devices for temperatures below 200 °C (392 °F), such as thermostats;
- Casings for screw or rivet joints between different metals;
- Bimetallic components and thermostatic bimetals where Invar is the passive component;
- Molds for producing carbon fiber reinforced plastics (CFP), especially in the aerospace industry;
- Structures for electronic control units in satellites and space equipment down to -200 °C (-328 °F);
- Support elements for electromagnetic lenses in laser control units;
- Flywheels;
- Automotive components;
- Transport of liquefied hydrogen;
- Optics and precision mechanics.

3.2 Aluminum

Aluminum oxide was discovered in the late 18th century, paving the way for aluminum production. However, it wasn't until the mid-19th century that small quantities of aluminum were produced and methods for its industrial production were developed. These methods were initially too complex and economically demanding. Later, in 1886, Paul (Louis-Toussaint) Héroult and Charles Martin Hall independently developed the process of extracting aluminum through the electrolysis of aluminum oxide. This method, with minor modifications, remains in use today.

Aluminum is a lightweight, silvery-white metal. It can be drawn into wires, rolled into thin sheets, and made into foils. Pure aluminum is processed through extrusion, drawing, and stamping. In electrical engineering, aluminum is used as a conductor and as a surface protection for iron (through alloying and caloization). It resists corrosion, and anodizing (electrolytic oxidation) can enhance surface hardness. It is also used in precision mechanics, measuring instruments, and other applications. Aluminum is employed in mirrors designed to reflect short-wavelength ultraviolet rays, such as those used in astronomical telescopes for photographing the sky. This is achieved by creating a thin layer of aluminum through vacuum deposition of aluminum vapor [2, 8].

3.2.1 Aluminum Alloys

Aluminum alloys, in contrast to pure aluminum, have significantly better mechanical properties. This advantage is especially evident in aerospace manufacturing, where aluminum alloys replace much heavier steel components [8].

The extensive development of alloy usage encompasses a wide variety of alloys based on chemical composition, application area, and processing methods [8].

Typically, aluminum alloys are divided into two main categories: wrought alloys and cast alloys. Both categories share common alloying elements. Some alloys lie at the boundary between these categories and can be used for both processing methods [8].

The basic binary aluminum alloys are Al-Cu, Al-Mg, Al-Mn, Al-Si, and Al-Zn. In these systems, aluminum forms a substitutional solid solution with the corresponding components, which is stronger and harder than pure aluminum while maintaining good formability and toughness [8].

This is reflected as follows:

Copper – increases the strength and hardness of the alloy but reduces its formability. In wrought alloys, copper typically makes up to 6 %, while in casting alloys, it can be up to 12 %. It adversely affects corrosion resistance [8].

Magnesium – appears in small amounts in almost all aluminum alloys. It primarily improves conditions for heat treatment and enhances corrosion resistance. The magnesium content is typically 8 % in wrought alloys and 11 % in cast alloys [8].

Manganese – improves strength, ductility, and corrosion resistance. At higher concentrations, it increases brittleness and worsens castability [8].

Zinc – provides greater strength, reduced toughness, and improved corrosion resistance. Low ductility at room temperature improves at higher temperatures [8].

Iron and Silicon – are common additives in aluminum. In alloys for forging, the iron content is up to 0.5 %, and in special cases, up to 1.6 %. In casting alloys, iron additions up to 1 % improve properties. Silicon content varies; casting alloys may contain up to 13 %, and in some cases, up to 25 % [8].

Nickel – increases mechanical properties at both normal and elevated temperatures and improves corrosion resistance [8].

Other elements such as chromium, cobalt, tungsten, titanium, vanadium, and zirconium, among others, positively influence the refinement of crystallization even in very small quantities. This is essentially the main reason for the use of these elements in aluminum alloys [8].

Tab. 2 Chemical Composition of Some Aluminum Alloys

Aluminum sheets and plates and their weight percentage of alloying elements (%)

ALUMINUM ALLOY	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	OSTATNÉ
EN AW 1050 A	0,25	0,4	0,05	0,01	-	0,01	0,07	0,05	0,03
EN AW 2017 A	0,20 - 0,80	0,7	3,50 -4,50	0,40 -1,00	-	0,10	0,25	0,25	0,15
EN AW 5005 A	0,20 - 0,80	0,7	3,50 -4,50	0,40 - 1,00	-	0,10	0,25	-	0,15
EN AW 5083	0,40	0,4	0,10	0,40 - 0,10	4,00 - 4,90	0,05 - 0,25	0,25	-	0,35
EN AW 5754	0,40	0,4	0,10	0,50	2,60 - 3,60	0,30	0,20	0,40	0,40
EN AW 6082	0,70 - 1,30	0,5	0,10	0,40 - 1,00	2,60 - 1,20	0,25	0,20	-	0,30
EN AW 7075	0,40	0,5	1,20 - 2,00	0,30	2,10 - 2,90	0,18 - 0,28	5,10 - 6,10	0,20	0,15
EN AC 5083	0,40	0,4	0,10	0,40 - 1,00	4,00 - 4,90	0,05 - 0,25	0,25	-	0,15

* Aluminum and common impurities make up the remainder

Source: [9].

Tab. 3 Basic Properties of alloy EN AW 5083

Density at 20°C	2660 kg./m3
Melting temperature	575-638°C
Coefficient of expansion at 20°C and 100°C	24,2 10-6 K-1
Hardness (HB)	Not specified
Modulus of elasticity at 20°C	70 GPa
Yield strength	110 MPa
Tensile strength	270 MPa

Source: [10].

Applications EN AW 5083

Most common applications [11]:

- Machinery: shipbuilding, welded structures, precision parts, molds, medium-load components, foaming molds, vehicle production.
- Construction: components where high corrosion resistance and medium strength are required.
- Chemical industry: tanks and parts where high corrosion resistance and medium strength are required.

3.3 Polyethylene (PE) and its Modifications

Polyethylene (PE), chemically known as poly(ethylene), is a thermoplastic polymer used in numerous technical applications. The annual production of PE reaches 60.10^9 kg. It is manufactured through the polymerization of ethylene. Various polymerization methods can be employed: radical polymerization, anionic or cationic addition polymerization, and ionic coordination polymerization. Each of these methods results in PE with different physical and mechanical properties [12].

Polyethylene (PE) is classified into several categories, primarily differing in terms of molecular weight, degree of chain branching, and density, which reflect their physical-mechanical properties [12].

Basic Classification:

- **UHMWPE** (Ultra High Molecular Weight PE): Ultra-high molecular weight polyethylene
- **HMWPE** (High Molecular Weight PE): High molecular weight polyethylene
- **HDPE** (High Density PE): High-density polyethylene
- **HDXLPE** (High Density Cross-Linked PE): Cross-linked high-density polyethylene
- **PEX** (Cross-Linked PE): Cross-linked polyethylene
- **MDPE** (Medium Density PE): Medium-density polyethylene
- **LDPE** (Low Density PE): Low-density polyethylene
- **LLDPE** (Linear Low Density PE): Linear low-density polyethylene
- **VLDPE** (Very Low Density PE): Very low-density polyethylene [12]

By comparing the properties of the mentioned polyethylene modifications, UHMWPE (Ultra High Molecular Weight Polyethylene) appears to be the best option for constructing a telescope, as it can also be used for the tube. This polymer has extremely long polymer chains with high molecular weight. The molecular weight of these chains and their low branching allow for very good chain packing into crystalline structures. As a result, UHMWPE is a very strong and tough material with the highest impact toughness among thermoplastics. UHMWPE exhibits excellent resistance to corrosive chemicals, except for oxidative acids. It has extremely low moisture absorption, a very low coefficient of friction, is self-lubricating, and highly resistant to abrasion (up to 10 times more resistant compared to carbon steel) [12].

The advantages of UHMWPE include excellent strength, toughness, and resistance to abrasion and chemicals. The disadvantage is that UHMWPE cannot be processed by melting, as thermal decomposition occurs before the polymer melts [12].

Applications of UHMWPE include fibers and textiles (fishing nets, bulletproof vests), bearings, gears and drives, artificial joints, moving parts of spinning and weaving machines, various protective strips, butcher's blocks, lining for chutes and slides for abrasive materials, and more [12].

Tab. 4 Properties of UHMWPE

Polyethylene (PE) UHMWPE

Density:	934 - 980 kg/m^3		
Crystallinity:	> 90 %		
Water absorption:	0,01 %		
Mechanical properties		**Physical properties**	
Young's modulus of elasticity:	0,7 GPa	Max. service temperature:	155 °C
Modulus of elasticity in bending:	0,75 GPa	Thermal conductivity:	0,403 - 0,435 W/m.K
Tensile strength:	35 - 40 MPa	Specific heat capacity:	1,8 - 1,88 kJ/kg.K
Yield strength:	18 - 29 MPa	Coefficient of thermal expansion:	125 - 200 .10^{-6}.K^{-1}
Elongation:	300 - 850 %	Flammability UL94:	HB
Extension at yield point:	25 %	Oxygen index:	17 %
Hardness (Rockwell R):	50	Electrical resistivity:	10^{18} Ω.cm
Fracture toughness:	1,4 - 1,7 MPa.m$^{1/2}$	Breakdown voltage:	28 MV/m
		Dielectric constant:	2,3
		Dissipation factor:	0,0002

Source: [13].

Applications UHMWPE

The most common uses [14]:

Bearings: Wear-resistant profiles and segments, chain guides.

Conveyor: conveyor elements, conveyor chutes, sliding conveyor liners, conveyor star wheels, antistatic sliding components, curved tracks, arcuate guides, conveyor belts.

Sliding elements: sliding rails, sliding profiles, sliding segments.

Other applications: scraper blades, containers, outlets, belt insulation, seals, guiding elements, sliding components, plain bearings, connecting belts, sliding parts with high wear resistance, chain guides, gears, crane foot support plates, bearing sleeves, pressing belts, pump components, belt guides, rollers for roller tracks, chain conveyors, conveyor chutes, deflection rollers, guiding rails, and workpiece carriers on conveyors [14].

4 CONCLUSION

In the environmental analysis, we must consider the changes in the parameters of the lenses, which result from variations in temperature and pressure. Such an affected system becomes the foundation for evaluating image quality. When monitoring changes in optical properties, we take into account the initial conditions:

- Nominal temperature of 20 °C;
- All spaces, including the object and image spaces, are filled with air under a pressure of 1013.25 × 10^9 Pa (sea level pressure);
- The refractive index of air is considered to be 1.0, which is the assumption stated in optical glass catalogs [15].

Any change in temperature will cause all glass elements to expand or contract according to the coefficient of thermal expansion. This will affect the radius of curvature, axial thickness, aperture radius, and aspheric coefficients according to the following relationship:

$$L(T + \Delta T) = (1 + \alpha . \Delta T) . L_0 \qquad (8)$$

where $\boldsymbol{L}$ is the length at the changed temperature, $\boldsymbol{T}$ is the reference temperature, $\boldsymbol{\Delta T}$ is the temperature change, and $\boldsymbol{\alpha}$ is the coefficient of linear expansion. All spaces filled with air will change due to heat according to the axial thicknesses, summing the individual thickness changes. If strongly curved surfaces are used in the optical system, the length of the spacers may significantly differ from the axial air space.

4.1 Assessment of the Impact of Heat on the Design of the Optical System

To meet certain thermal performance requirements of the optical system, such as athermalization, it is sometimes necessary to use special mounting techniques, where individual lenses or groups of lenses are secured in separate housings. Materials with abnormal coefficients of thermal expansion are often used for these housings in order to maintain image focus without any focusing mechanism (so-called passive athermalization) [15].

With temperature changes, lenses or even entire lens groups may shift relative to other surfaces, typically different from the immediately preceding one. As a result, the space between two lenses changes, which is not dependent on the thermal expansion coefficient of the housing material but rather on a more complex principle [15].

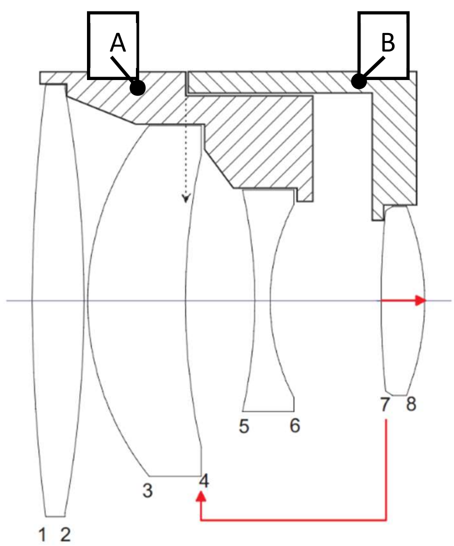

Fig. 3 The Effect of Thermal Expansion on Global Reference Surfaces
Source: [15].

In Figure 3, a simple optical system is illustrated where the final lens of the system, with surfaces 7-8, is mounted in a separate housing **B** attached to a flange on the main housing **A** at the surface 4 of the second lens. If the main and secondary housings were made from different materials, the space between the third and fourth lenses would vary according to the difference in thermal expansion of these two materials [15].

Given these considerations, it is crucial to focus on the appropriate selection of materials for optical instruments. The most important factor is to choose an optimal material for optical elements so that thermal effects minimally impact image quality. Subsequently, it is essential to select a tube or housing material for the optical system that either minimizes the resulting changes or compensates for them through the beneficial effects of thermal expansion of the material.

4.2 Comparison of the Thermal Expansion of Selected Materials

After examining the properties of the materials discussed in the paper and considering them as the most promising for the construction of the targeting telescope body, and subsequently comparing the material data sheets and cited sources, I can conclude the following:

The coefficient of thermal expansion is the most important parameter that has the greatest impact on the quality and accuracy of imaging in optical systems.

The materials have the following coefficients of thermal expansion:

Invar alloy FeNi36	$1{,}2.10^{-6}$ K^{-1}
Aluminum alloy EN AW 5083	$24{,}2.\ 10^{-6}$ K^{-1}
Polyethylene (PE) UHMWPE	$125 - 200\ .10^{-6}$ K^{-1}

From this, it follows that the material with the lowest coefficient of thermal expansion, relative to the same coefficient of expansion of the glass used in the optical system, is the most suitable. In this case, Invar is the most frequently used material in optical systems due to this physical property. However, since the optical systems of targeting telescopes are complex assemblies of several lens groups, other materials can be considered as compensatory elements for passive athermalization.

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