Functional Materials 13, No.1 (2006)

Selection criteria for materials to be applied in cryogenic precision equipment engineering

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Received July 7, 2005

Experimental data on temperature effects on the Maksutov coefficient being a preliminary criterion of the material suitability for astro-mirror manufacturing have been summarized for materials of promise for cryogenic optical systems and precision equipment. The material that meets the cryogenic optics requirements to the greatest extent has been noted. Experimental data on low-temperature cycling and dimensional stability of materials used in the field of measuring engineering have been analyzed.

Для материалов, перспективных в криогенных оптических системах и прецизионных устройствах, обобщены экспериментальные данные по влиянию температуры на коэффициент Максутова, являющийся предварительным критерием пригодности материала для изготовления астрозеркал. Отмечается, какой из них по комбинации свойств лучше удовлетворяет требованиям криогенной оптики. Рассмотрены экспериментальные данные по низкотемпературному циклированию и размерной стабильности материалов, используемых в измерительной технике.

The long-term operability of precision cryogenic equipment is a problem of great importance in physical materials science. The materials used in manufacturing of precision optical systems and navigation gyroscopes are subjected to extreme external factors resulting in considerable changes in physical and mechanical properties thereof. At the same time, there are no criteria to select a material usable in precision cryogenic engineering because the problem is highly complicated. The only suitable criterion for the material selection taking into account the set of its physical and mechanical properties is the empirical Maksutov coefficient [1] derived from the shape stability condition under low mechanical stresses and temperature gradients acting on the material: $P = E\lambda/(\alpha C\rho)$ where E is the Young modulus; λ, heat conductivity; α, thermal linear expansion coefficient; C, specific heat capacity; ρ, the material density. The higher is the P value, the more preferable is the material in manufacturing of the precision optical systems. However, the Maksutov coefficient was used up to now mainly near room temperature. As to low-temperature region, there are only scarce literature data on P [2–4]. In this connection, the purpose of this work is to obtain and investigate the low-temperature $P(T)$ dependences for materials of promise in the precision engineering as well as the criteria depending on the material structure state.

Polycrystalline beryllium, five industrial aluminum alloys, nonmetal materials (SO115M glass ceramics, dross-cast silicon carbide, polycrystalline cast silicon) and some others materials were studied. Basing on temperature dependences of physical and mechanical properties as well as on literature data, the P values have been calculated within 30 to 300 K temperature range. To analyze the mechanical and thermal conditions of operability for materials under study, the dimensional stability under force and temperature cycling was measured. Using the method described in [5, 6], we

Table. Temperature dependence of Maksutov coefficient for some materials of promise in cryogenic optics

Material	T, K			
	30	77	200	300
Beryllium	$891\cdot10^3$	22100	448	134
ABM-1	1635	378	61	36
SAS1-400	$13.14\cdot10^3$	472	73	52
AMg6	5590	51	19	17
Al–Zn alloy	2880	57	21	19
AK-25	8527	222	50	39
AM4K2	7832	235	31	27
Silicon	$23.96\cdot10^6$	$1.34\cdot10^5$	2400	599
Silicon carbide	$15.7\cdot10^5$	$33.37\cdot10^5$	$18.31\cdot10^3$	1127
SO115M glass ceramics	12	10	34	19

succeeded in measuring of dimensional instability at an error of about 10^{-6} under low-temperature thermal cycling and low stresses (up to the yield limit). The method consists in measuring of linear dimensions of two specimens by measuring the gap between those. The setup for dimensional stability measurements includes a bath for thermal cycling, a bench made of SO115M glass ceramics, two specimens having the total length L = 250 mm and a NU-2E optical microscope [7]. The gap width (δ = 50 μm) between the specimens was measured prior to and after the thermal cycling at an error about 0.5 μm. The δ value was measured at 273 K. The measurement error is due mainly to the inaccuracy of the microscope focusing at the specimen surface. In that connection, the measurement error was determined as the r.m.s. within a series of 15 control measurements. The relative change in the specimen dimensions was determined as the ratio $\varepsilon = \delta L/L$ where L is the change in the gap width δ between the specimens.

It is to note that the thermal and force cycling methods were elaborated mainly for use at high temperatures. The low-temperature thermal cycling has some specific features associated with the fact that the specimens are cooled as a rule by immersion thereof into a cryogenic liquid. That results in formation of considerable temperature gradients causing high internal stresses. The loading device is cooled in part together with the specimen, thus complicating the measurements of stresses and strains. To date, only few constructions of devices for thermal cycling of materials at low and super-low temperatures are known [8–10]. The experiments on low-temperature thermal cycling treatment (LTCT) were carried out using the setup [10] providing the thermal cycling at as low temperatures as 4.2 K under programmed loading and cooling of the specimens.

Table presents the P values calculated from temperature dependences of physico-mechanical properties for 10 various materials, some of those being used in manufacturing of cryo-mirrors and other assemblies of cryogenic optics. The temperature lowering down to 30 K is seen to result in an appreciable increase of the coefficient P for all the materials studied except for SO115M glass ceramics. The P values increase in different manner for diverse materials and non-monotonously in many cases. The Maksutov coefficients at T = 300 K decrease in the following sequence: SiC, Si, Be, SAS-1, AK-25, ABM-1, etc. As to the use of materials in UR spectroscopy at T = 30 K, the greatest increase in P is observed mainly for few materials, namely, Si, SiC, Be, and SAS1-400. Consideration of temperature dependences of characteristics included in the empirical formula of the Maksutov coefficient shows that the presence of a maximum in P value for SiC at 77 K as well as that for the glass ceramics at 200 K is defined substantially by the run of heat conductivity λ and expansion coefficient α temperature dependences. So for SiC, the λ starts to decrease at 77 K while α drops abruptly and attains a minimum at T = 30 K. Similar non-monotonous changes in thermophysical parameters are typical also of the glass ceramics: λ_{max}, α_{max} at 200 K, λ_{min}, α_{min} at 77 K.

When comparing the data from Table, it is seen that the highest P values are characteristic for Si, SiC, and Be. However, considering other properties of those materials, it is clear that some of those do not meet certain requirements defining the material suitability for the cryo-mirrors, namely, the isotropy and structure stability under thermal cycling and external stresses lower than the macroscale yield limit at corresponding temperatures. In this connection, it is to pay attention to the dimensional and structural stability of materials selected basing on the $P(T)$ maximum criterion. The study of the material dimensional stability should be combined with investigation of the material structure state and its evolution.

The changes in the material structure and properties under thermal and force cycling depend on numerous factors that can be subdivided into internal and external ones. The former include the metal or alloy crystal lattice type, the initial structure state, the material thermophysical properties, its inclination to phase transformations, the dislocation stacking defect energy, the anisotropy extent of the material physical properties, and the acting plastic strain types (sliding, twinning, etc.). The external factors include the specimen (or piece) shape and the thermal and force cycling parameters (the temperature gradient, the heating/cooling rate, the holding time at a specific temperature, the presence or absence of external loading, etc.). The stresses arising at the thermal and mechanical treatment of a material may relax in various ways, depending on a combination of the external and internal factors. This causes various characters of the structure state formation and thus the dimensional stability and other structure-sensitive physical properties.

Among the materials mentioned in Table, it is just Si that shows the highest value of the Maksutov coefficient. That is why it is of a great importance to consider problems associated with other properties of the material that define its suitability for astrophysical instruments being operated in the appropriate low temperature range, in particular, its dimensional stability under LTCT. The experiments carried out on Si specimens have shown that the cast silicon specimens are dimensionally unstable. A repeated heat treatment favors the stabilization of the material behavior under LTCT. Nevertheless, a residual strain of about 10^{-4} arises in the cast silicon specimens during the thermal cycling. That strain is not associated with twinning that could be expected at low-temperature cycling; but perhaps it is due to pores the density of which decreases as the number of thermal cycles increases.

The stresses arising under the LTCT of materials used in the cryogenic UR optics are caused by the hindrances to their thermal expansion (contraction). The highest thermal stresses are formed if the material is subjected to a temperature gradient (thermal shock). Such conditions arise when a material being at a homogeneous temperature is immersed into a medium of a different temperature. In this case, the first order stresses may arise which become equilibrated within limits of the body. In polycrystals or composites, the free dimensional change of individual grains due to temperature variations is hindered by different orientation of the grains (the composite constituents). In this case, the second order stresses arise and are equilibrated within limits of the grain size. The thermally induced stresses increase in proportion to the hindered strain right up to the elasticity limit.

Thus, the comparative consideration of data on the Maksutov coefficient, the dimensional and structure stability has shown that it is just the cast silicon that is the most suitable material for astronomic mirrors and gyroscope elements of astrophysical UR optical equipment. Its advantages include a relatively high strength, ultrahigh heat conductivity, and small thermal expansion. The drawbacks of the material are porosity, the presence of internal stresses in as-cast blanks and dimensional instability ($\varepsilon_{res}\approx 10^{-4}$). Nevertheless, the available information on stabilizing effect of heat treatment allow us to expect for elimination or at least reduction of those drawbacks.

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Критерії відбору матеріалів для використовування у криогенній прецизійній техніці

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Для матеріалів, перспективних у кріогенних оптичних системах та прецизійних пристроях, узагальнено експериментальні дані щодо впливу температури на коефіцієнт Максутова, що становить попередній критерій придатності матеріалу для виготовлення астродзеркал. Відзначається, який з них за комбінацією властивостей ліпше відповідає вимогам криогенної оптики. Розглянуто експериментальні дані щодо циклування і розмірної стабільності матеріалів, що використовуються у вимірювальній техніці.