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Research article
Научная статья

Analysis of the slurry and ceramic properties for investment casting obtained with domestic colloidal silica binders

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Abstract: The quality of cast parts produced by investment casting is largely determined by the quality of the ceramic molds. Currently, aircraft and engine building enterprises are switching to an environmentally friendly colloidal silica binders for the manufacture of ceramic molds. In this work, the dynamic and relative viscosity of slurries prepared using fused silica powder and colloidal silica binders of the VT13-02U (Vakuumteh LLC), Stavroform VS (Polymet LLC), UltraCast One + and UltraCast Prime (both Technopark LLC) manufacturers were determined. It is shown that the slurries prepared on the considered binders have similar viscosity values, and in their rheological properties they are close to Newtonian liquids. The values of dynamic and relative viscosity at a binder content of 400 mL per 1 kg of fused silica powder were ~732 mPa·s and ~380 s, respectively. With an increase in the binder content to 600 mL per 1 kg of fused silica powder, the dynamic and relative viscosity decreased to ~70 mPa·s and ~16 s, respectively. An equation was also found that relates the dynamic viscosity determined using a rotational viscometer and the relative viscosity determined using the VZ-4 viscosimeter. The mechanical properties were determined during three-point bending tests on ceramic samples obtained using slurries on the above-mentioned colloidal silica binders and fused silica stucco. Samples obtained on binders VT13-02U, Stavroform VS and UltraCast One+ showed very similar bending strength values, namely 3.5–4.3 MPa after drying and 5.8–6.1 MPa after firing. Due to the presence of a polymer addition in the binder, the ceramic samples obtained on the UltraCast Prime binder had higher values of bending strength after drying and after firing – 6.4 and 7.2 MPa, respectively. It was also shown that with an increase in the viscosity of the slurry and a decrease in the fraction of fused silica stucco, the strength of the samples increases. The lowest surface roughness was observed for samples obtained with UltraCast grade binders.

Keywords: investment casting, nickel superalloy castings, colloidal silica binder, fused silica powder, slurry, viscosity, mechanical properties

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Анализ свойств суспензии и керамики для литья по выплавляемым моделям, полученных на отечественных связующих на водной основе

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Аннотация: Качество литых деталей, изготовленных методом литья по выплавляемым моделям, в значительной мере определяется качеством керамических форм. В настоящее время предприятия авиа- и двигателестроения переходят на экологически безопасное водное связующее для изготовления керамических форм. В работе определены динамическая и условная вязкости суспензий, приготовленных с использованием пылевидного плавленого кварца и отечественных водных связующих марок ВТ13-02У (ООО «Вакуумтех»), Ставроформ ВС (ООО «Полимет»), UltraCast One+ и UltraCast Prime (ООО «Технопарк»). Показано, что полученные суспензии имеют близкие значения вязкости и по своим реологическим свойствам близки к ньютоновским жидкостям. Значения динамической и условной вязкости при содержании связующего 400 мл на 1 кг пылевидного кварца составили ~732 мПа·с и ~380 с соответственно. При увеличении содержания связующего до 600 мл на 1 кг пылевидного кварца вязкость снизилась до ~70 мПа·с и ~16 с соответственно. Также было выведено уравнение, связывающее динамическую вязкость, определенную с помощью ротационного вискозиметра, и условную вязкость, установленную с помощью прибора ВЗ-4. Были определены механические свойства при испытаниях на трехточечный изгиб керамических образцов, полученных с использованием суспензий на указанных выше связующих и обсыпки из плавленого кварца. Образцы, полученные на связующих ВТ13-02У, Ставроформ ВС и UltraCast One+, показали очень близкие значения прочности: 3,5–4,3 МПа после сушки и 5,8–6,1 МПа после прокалки. Из-за наличия в составе связующего полимерной добавки керамические образцы на связующем UltraCast Prime имели более высокие значения прочности на изгиб после сушки и после прокалки – 6,4 и 7,2 МПа соответственно. Также было показано, что с увеличением вязкости суспензии и уменьшением фракции плавленого кварца прочность керамических образцов возрастает. Из всех рассмотренных связующих наименьшая шероховатость поверхности наблюдалась у образцов, полученных с использованием связующих UltraCast.

Ключевые слова: литье по выплавляемым моделям, жаропрочные никелевые отливки, водные связующие, пылевидный кварц плавленый (ПКП), суспензия, вязкость, механические свойства

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Introduction

Casting quality plays a critical role in ensuring the overall reliability of an aircraft engine. One of the key determinants of casting quality is the quality of ceramic molds used in the investment casting process. These molds must be of high quality to produce castings with high dimension accuracy and smooth surface finishes.

Two binders are commonly used for making ceramic molds for investment casting of large nickel superalloy parts. The first binder is based on a hydrolyzed

solution of ethyl silicate, which is typically dissolved in ethanol or a mixture of ethanol and isopropanol. The second binder is an aqueous colloidal solution of silica [3]. Currently, foundries are increasingly adopting aqueous colloidal silica binders [4]. These binders contain Na-stabilized amorphous SiO_2 particles, which form silica gel as moisture is removed, thereby bonding the stucco particles together to create the ceramic mold [5—7].

Binders containing hydrolyzed ethyl silicate solutions are unsuitable for advanced, unattended foundries because organic solvents used in these binders are highly flammable. The latest environmental regulations ban the use of ethyl silicate due to health hazards associated with the organic solvents and ammonia vapors used in the curing of ceramic molds [5, 7, 8]. In contrast, aqueous colloidal silica binders are environmentally friendly and well-suited for unattended production facilities. Additionally, they are cost-effective and can reduce casting costs [9—12].

Fused silica powder (FSP) can be used as a component of slurry to make ceramic molds for casting large nickel superalloy parts. Fused silica (FS) with various particle sizes is used as stucco [13, 14]. Alumina is not typically used as stucco for large castings due to its high density which can result in overly heavy molds. Fused (amorphous) silica is preferred because it has a thermal expansion coefficient that is approximately 27 times less than that of crystalline silica [15, 16].

However, colloidal silica binders have some disadvantages compared with hydrolyzed ethyl silicate binders, including a tendency to sedimentation, slow drying of the slurry, and poor wettability of wax clusters [10]. To address these issues, additional components such as polymers, surfactants, defoamers, anti-gelling agents, and ceramic shell drying indicators are added to the slurry, and sometimes to the binder [17]. Despite these drawbacks, ceramics made with advanced hydrolyzed ethyl silicate or a colloidal silica binders exhibit similar strengths [5].

The viscosity of the slurry for the first ceramic shell layer is a crucial factor affecting the surface quality of the mold [18, 19]. An increase in dynamic viscosity of the slurry results in thicker layer, which can complicate drying and lead to mold cracking [20]. The dynamic viscosity of the slurry is influenced by factors such as temperature, stucco fraction and stucco particle size distribution [20].

Strength is the primary property of the ceramic mold. The mold must be sufficiently robust before firing in order to allow pattern removal, and after firing in order to bear the weight of the liquid metal. However, the strength after firing should not be excessive to avoid hot tearing in alloys and to facilitate mold knockout [3, 21]. The strength of the shell mold is directly dependent on slurry properties, as well as the technology employed in slurry preparation and application. If there is insufficient wetting of the slurry filler with the binder, the shells may not reach the required strength and could crack [19].

The use of colloidal silica binders without any additives results in very low strength of the green (unfired) molds, which are prone to cracking during wax pattern removal and other processes. For this reason, liquid polymer additives, such as either latex (for alkaline binders) or polyvinyl acetate (PVA) based (for acidic binders) are commonly used [21, 22].

The gas permeability of the ceramic mold is affected by the particle size of the stucco used. The permeability of the first layer is particularly important [22]. Therefore, it is crucial to examine the viscosity of the slurry and the strength of ceramic mold samples made using stuccos with varying particle size distributions.

Currently, domestic manufacturers utilize casting equipment from the leading global vendors. The equipment is designed to work with imported binders exclusively. However, high-quality binders from domestic vendors are available on the market. The aim of this study is to evaluate the viscosity of the slurries made with domestic colloidal silica binders and analyze the impact of refractory particle size in stucco on the mechanical properties and surface finish of ceramic molds.

Materials and methods

Analysis of binder properties. Preparation of slurries and viscosity measurements

We utilized four types of aqueous binders manufactured in Russia, namely VT13-02U (Vakuumtech, Moscow), Stavroform VS (Polymet, Togliatti), UltraCast One+, and UltraCast Prime (Technopark, Moscow), to prepare the slurries. To determine the density of the binders, we weighed on analytic scale a known volume (50 mL) of each binder using a burette. The pH of the binders was measured using a HI83141 pH meter from Hanna Instruments (USA).

The slurries were prepared by mixing 400 mL of the aforementioned binders with 1 kg of FSP with a particle size of 0.045 mm (Kefron, Russia). After mixing, the slurry was allowed to incubate for 24 h to ensure proper wetting of the FSP particles with

the binder and to release any trapped air. Then it was stirred for 10 min to uniformly distribute the FSP particles. The viscosity of the slurry was measured and after the 50 mL of binder was added. This enable us to determine the viscosity of the slurry containing 400, 450, 500, 550, and 600 mL of the binder per 1 kg of FSP.

To measure the viscosity of the slurries, we used two different viscosity measurements procedures.

1. The relative viscosity was estimated using a VZ-4 capillary tube viscometer (nozzle diameter and cup height: 4 mm) according to state standard GOST 9070-75. The relative viscosity is directly proportional to the slurry flow time. Each measurement was repeated 2—3 times.

2. The dynamic viscosity was measured using a DV2TLV rotary viscometer (Brookfield, USA). The slurry (binder) was poured into a 400 mL glass beaker. We used LV-1 (#61) and LV-3 (#63) spindles for a 15—400)·10^3 mPa·s viscosity range [23]. The spindle rpm ranged from 10 to 200.

Particle size measurements of fused silica powder and fused silica refractory

We conducted an estimation of the particle size distribution of FS by employing a set of sieves in accordance with GOST 29234.3-91 state standards. Specifically, a 01412 vibration sieve (Litmashpribor Usman Foundry Equipment Company, Russia) was utilized for this purpose.

To determine the particle size distribution of the FSP we used microphotographs taken with a Vega 3 SBH scanning electron microscope (Tescan, Czech Republic). We measured particle areas on the microphotographs with the aid of ImageJ 1.52a software (National Institutes of Health, USA). This software computed particle diameter and volume based on their areas. After that, we determined the volume fraction of particles within each size range.

Manufacturing the samples. Three-point bending tests. Roughness measurements

We prepared ceramic square samples for bending tests [24]. The slurry was made with VT13-02U, Stavroform VS, UltraCast One+, and UltraCast Prime binders with 20, 40, and 60 seconds relative viscosity, as measured by the VZ-4 viscometer. The wax pattern made of the paraffin/stearin 50/50 compound (Fig. 1) was coated with the slurry and dust by stucco of fused silica grades FS 0.25—0.4 mm, FS 0.4—0.6 mm, and FS 0.5—1.0 mm (Kefron, Russia). The applied slurry and stucco were removed from the upper face (surface *A*) of the wax pattern with a knife. The ceramic sample was formed in cavity *B*. Each layer was air-dried at room temperature for 2 h. The number of layers varied from 5 to 9 depending on the slurry viscosity and the FS particle size.

The wax pattern was removed in boiling water. We produced six 40±1×20±1×8±1 mm ceramic samples for each FS particle size range (FS 0.25—0.4 mm; FS 0.4—0.6 mm, and FS 0.5—1.0 mm grades) and relative viscosity of the slurry (20, 40 and 60 s). Three of the six samples produsd as a single

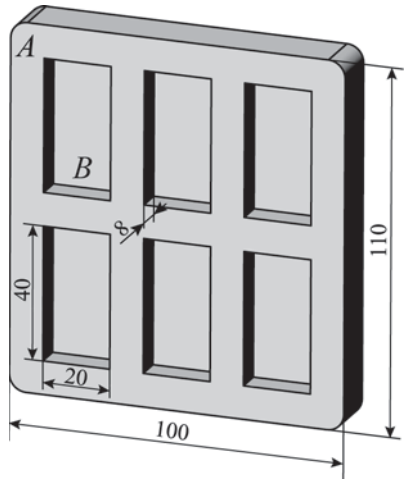

Fig. 1. Wax pattern for the production of ceramic samples

Рис. 1. Восковая модель для получения керамических образцов

Fig. 2. Ceramic samples for the mechanical tests after firing

Рис. 2. Керамические образцы после прокалки для механических испытаний

batch underwent firing as follows: heated to 900 °C over 1.5 h, held at this temperature for 2 h, and cooled in the furnace with the door open. The remaining three samples were tested before firing ("green") after air drying for 24 h. Fig. 2 illustretes the samples after firing.

We employed a 5966 universal testing machine (Instron, USA) to conduct three-point bending tests in accordance with the ASTM C1161-13 standard. The distance between the supports was set at 21 mm, and the loading rate was maintained at 1 mm/min.

The surface roughness of the samples was assessed using an M300C profilometer (MarSurf, Germany).

Results and discussion

Properties of the binders

The table presents the density and pH levels of the binders. The density values are nearly identical, falling between 1.15—1.16 g/cm^3. The pH values, which range from 9.8 to 10.6, confirm the alkaline nature of the binders. It is worth noting that the measured density and pH values fall within the ranges specified by the manufacturers.

The density and pH of investigated binders

Плотность и величина pH исследуемых связующих

Binder	Density, g/cm^3	pH
VT13-02U	1.16	9.8
Stavroform VS	1.15	10.2
UltraCast One+	1.16	10.6
UltraCast Prime	1.15	10.3

Particle Size Distribution of the FSP and FS

In Fig. 3, *a* the particle volume fractions of the FSP 0.045 mm grade fused silica powder are presented. The particles exhibit a size of 0 to 60 μm. Their size distribution is irregular, deviating from a normal distribution.

In Fig. 3, *b* the sieving residue for the FS are depicted. The FS 0.25—0.4 mm and FS 0.4—0.6 mm

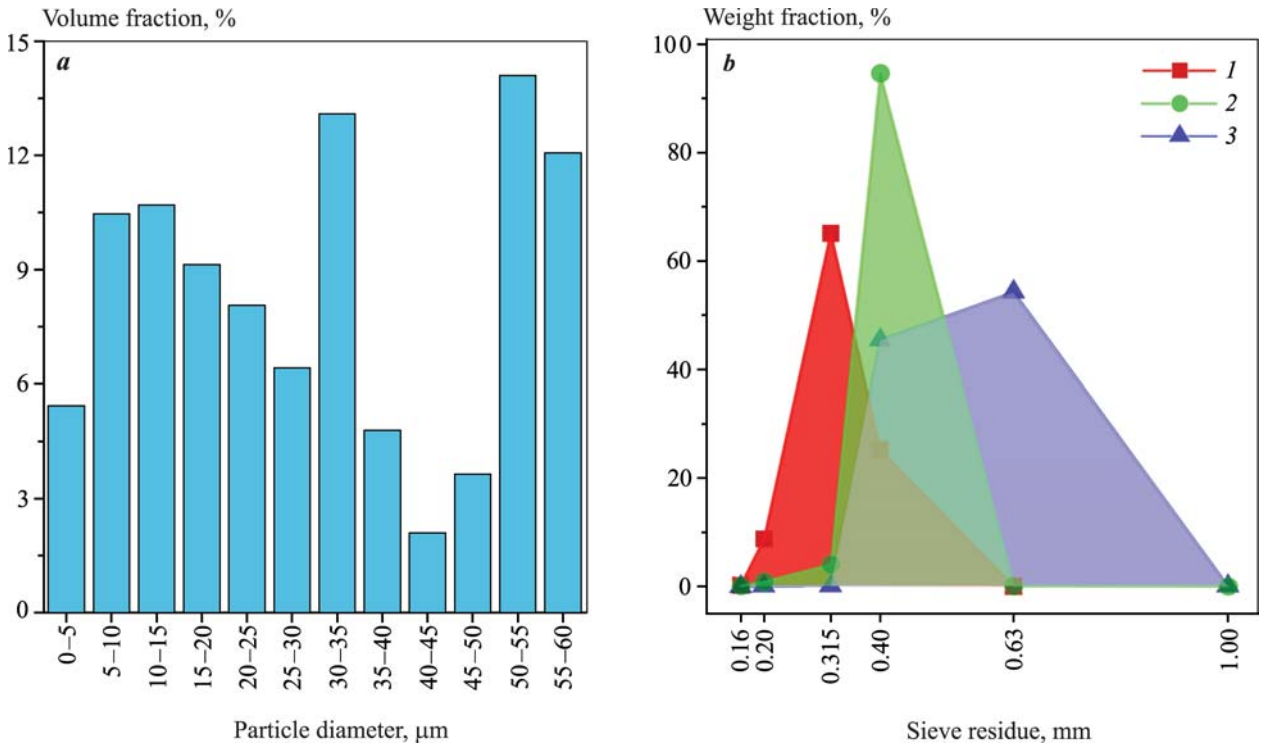

Fig. 3. Distribution of FSP 0.045 mm silica powder particles by size (***a***) and fused silica sieve analysis results (***b***)
1 – FS 0.25–0.4 mm, ***2*** – FS 0.4–0.6 mm, ***3*** – FS 0.5–1.0 mm

Рис. 3. Распределение частиц по размерам в пылевидном плавленом кварце ПКП 0,045 мм (***a***) и результаты рассева плавленого кварца на ситах (***b***)
1 – ПК 0,25–0,4 мм, ***2*** – ПК 0,4–0,6 мм, ***3*** – ПК 0,5–1,0 мм

grade refractories show that the bulk of the material is retained on the 0.315 and 0.4 mm sieves, which conforms to the FS specifications. For the 0.5—1.0 mm fused silica, its particles are distributed almost equally between the 0.4 and 0.63 mm sieves and the measured values are in line with the FS 0.5—1.0 mm grade specifications.

Slurry and binder viscosity measurements

In Fig. 4 the slurry viscosity is plotted against the binder content (in mL) per 1 kg of fused silica powder, with the viscosity of the binders indicated. The viscosity was measured using a rotational viscometer. The viscosity of the binders increased as the spindle rpm increased, indicating that they behave like non-Newtonian fluids. No significant difference was detected between the viscosities of the binders, which fell within the range of 6—8 mPa·s for 75 rpm (v), and 11—13 mPa·s for v = = 200 rpm. It is known that binders are non-Newtonian fluids, and their viscosity decreases as the shear rate increases [20]. However, we observed an inverse relationship, which may be attributed to the flow turbulence at high spindle speeds.

It is known that a higher binder viscosity leads to a higher slurry viscosity for the same filler/binder ratio [25]. In our study, the viscosities of the binders were almost the same. The authors of [20] investigated the viscosity of the Ludox SK binder using a similar method, and obtained a fairly close value of 7 mPa·s. As shown in Fig. 4, the slurry viscosity remains almost unaffected by the spindle speed, except for the low range (up to 50 rpm), indicating that the slurries behave like Newtonian fluids.

In order to determine the slurry viscosity, the average viscosity over the range of 50—200 rpm was taken since the viscosity did not change much in this range. Fig. 5, *a* illustrates the relationship between the viscosity of the slurries and the binder content, expressed in mL per 1 kg of FSP. It can be observed that the slurries containing the majority of the binders have comparable viscosities. The viscosity versus binder content relationship follows a logarithmic trend, as shown by the nearly linear curve plotted in a logarithmic scale. However, the VT13-02U grade binder exhibits a steeper curve, and slightly lower viscosity values. It is worth noting that all the binders have a similar SiO_2 content, and any variations in the viscosity of the slurries could be due the addition of polymers or other additives to the binder [26].

The cause of the viscosity variations could not be reliably determine. Studies [27, 28] have suggested that as the mixing time increases, the slurry viscosity also increases due to water evaporation into the environment and the friction heat generated in the slurry and in the mixer. Temperature and humidity fluctuations in the test room may also contribute to the viscosity differences, particularly for colloidal silica binder slurries, as they lead to non-uniform evaporation of water and non-uniform viscosity changes. Typically, the differences in the slurry viscosities are attributed to the densities and viscosities of the binders, with the latter having a greater impact on the viscosity of the slurry mixture than the density [25]. However, in this study, the viscosities and densities of the binders are very similar, indicating that the viscosities of the slurries containing different binders will be approximately equal.

It is widely recognized that the viscosity of the slurry increases in proportion with the ratio of filler to binder [25]. Specifically, when the binder content is increased from 400 to 600 mL per 1 kg of fused silica powder, the resulting viscosity drops from 550—870 to 60—80 mPa·s, respectively, indicating tenfold decrease. This viscosity level determines the velocity and uniformity of the slurry's flow over a pattern or underlying ceramic layer [17], and higher viscosity levels produce a thicker first layer [25].

Relative viscosity, as measured by the slurry flow time through a nozzle of a specific diameter, is a standard metric used in the casting industry. Fig.5, *b* displays the relative viscosity values of slurries measured using the VZ-4 viscometer. The viscosities of all slurries are near similar, with the exception of the VT13-02U binder, which was also observed in rotary viscometer readings. However, in this case, the rotary viscometer readings were lower than those of the other binders, whereas the VZ-4 viscometer readings were significantly higher.

We can infer from these observations that the relationship between viscosity and binder content (in mL) per 1 kg of FSP is non-linear. At higher binder contents, the rate of viscosity change decreases. Increasing the binder content from 400 to 600 mL per 1 kg of fused silica powder leads to a viscosity drop from ~380 to ~16 s, respectively, or about a 24-fold decrease.

Casting specifications typically call for relative viscosity levels between 20 and 70 s, depending on the layer number. Higher viscosity levels are required for the first layers, with viscosity levels decreasing in subsequent layers. A high viscosity results in a thicker and denser layer, which is particularly important when wetting is insufficient during the application of the first

layer [25, 27]. Additionally, high slurry viscosity provides a smooth finish for the first layer [27]. Previous research has shown [18] that when the relative viscosity of a slurry falls below 35 s, surface defects occur in the ceramic mold, regardless of the fused silica stucco grain size. To achieve a defect-free ceramic surface, it is necessary to increase slurry viscosity and decrease the stucco particle size.

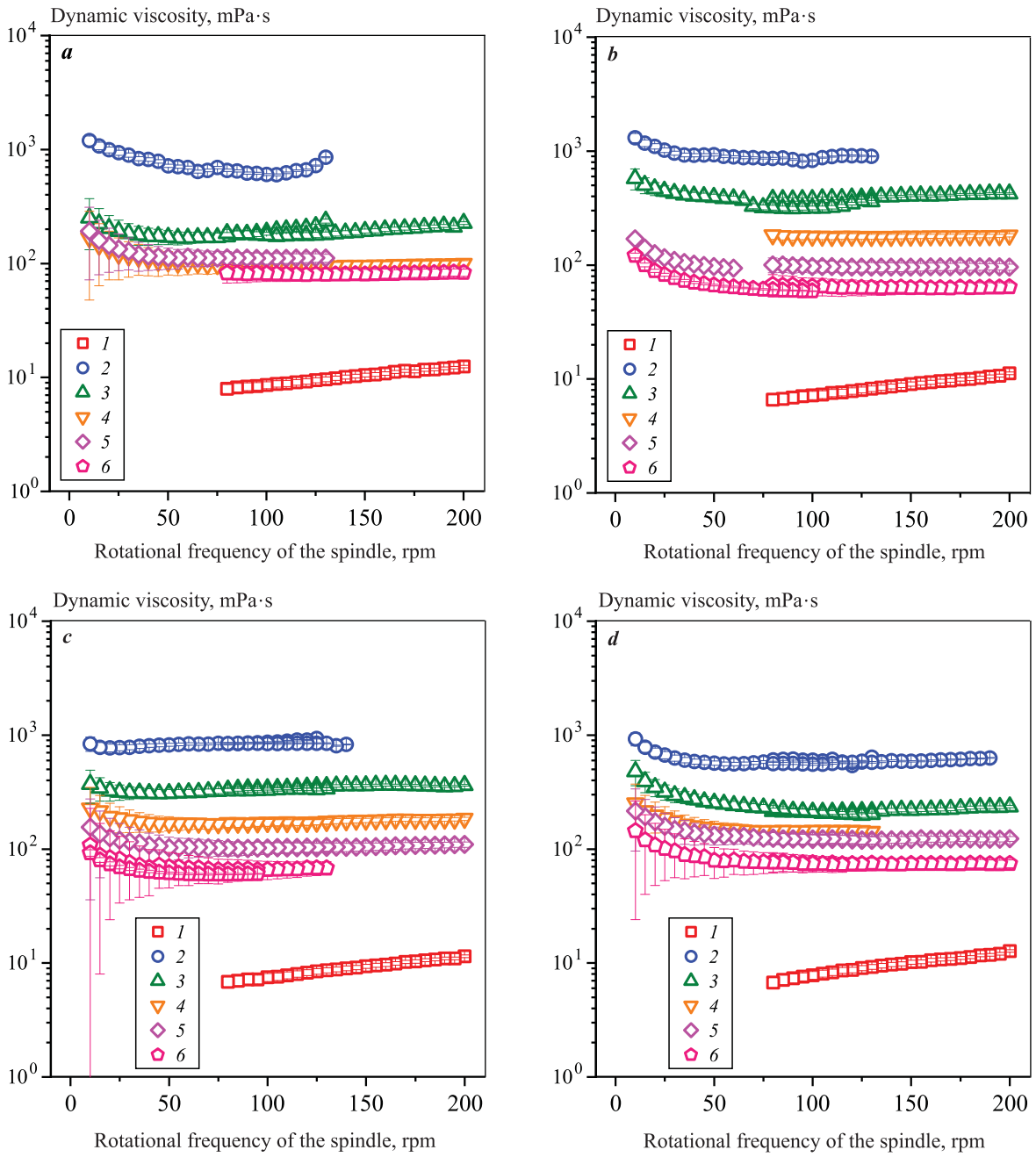

Fig. 4. Viscosity of slurry prepared with binders: VT13-02U (***a***), Stavroform VS (***b***), UltraCast One+ (***c***), UltraCast Prime (***d***), depending on the amount of binder

1 – binder without refractory, ***2*** – 400 mL, ***3*** – 450 mL, ***4*** – 500 mL, ***5*** – 550 mL, ***6*** – 600 mL
The amount of binder is given per 1 kg of silica powder

Рис. 4. Вязкость суспензии, приготовленной на связующих ВТ13-02У (***a***), Ставроформ ВС (***b***), UltraCast One+ (***c***) и UltraCast Prime (***d***), в зависимости от количества связующего

1 – связующее без наполнителя, ***2*** – 400 мл, ***3*** – 450 мл, ***4*** – 500 мл, ***5*** – 550 мл, 6 – 600 мл
Количество связующего приведено на 1 кг пылевидного кварцевого микропорошка

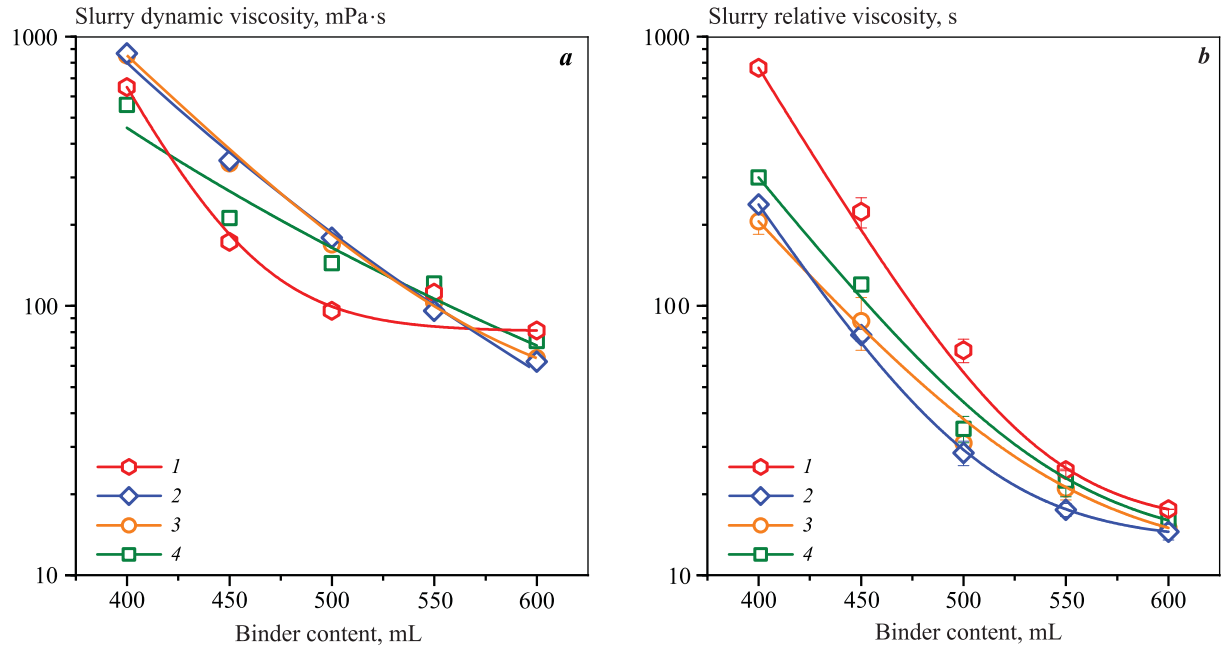

Fig. 5. The viscosity of the slurry, determined using the rotational viscosimeter (***a***) and a VZ-4 viscosimeter (***b***), depending on the content of the binder per 1 kg of silica powder

1 – VT13-02U, ***2*** – Stavroform VS, ***3*** – UltraCast One+, ***4*** – UltraCast Prime

Рис. 5. Вязкость суспензии, определенная с помощью ротационного вискозиметра (***a***) и вискозиметра ВЗ-4 (***b***), в зависимости от содержания связующего на 1 кг микропорошка

1 – ВТ13-02У, ***2*** – Ставроформ ВС, ***3*** – UltraCast One+, ***4*** – UltraCast Prime

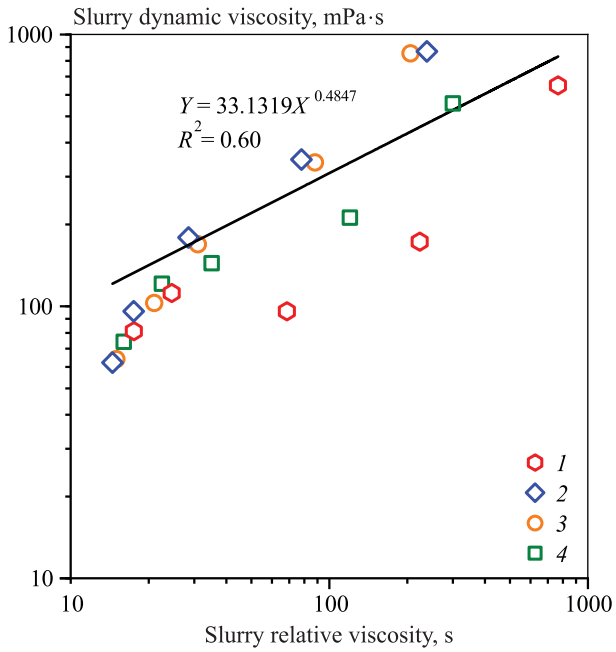

Fig. 6. Comparison of the viscosity of the slurry, determined using the VZ-4 viscosimeter (X) and a rotational viscosimeter (Y)

1 – VT13-02U, ***2*** – Stavroform VS, ***3*** – UltraCast One+, ***4*** – UltraCast Prime

Рис. 6. Соотношение между значениями вязкости суспензии, определенными с помощью вискозиметра ВЗ-4 (X) и ротационного вискозиметра (Y)

1 – ВТ13-02У, ***2*** – Ставроформ ВС, ***3*** – UltraCast One+, ***4*** – UltraCast Prime

A binder content ranging from 450 to 600 mL per 1 kg of FSP produces a slurry with a relative viscosity within the recommended range (20—70 s).

Since we have measured both the relative viscosity (using the VZ-4 viscometer) and the dynamic viscosity (using the rotary viscometer), it is worthwhile to examine the correlation between these two parameters for the slurries investigated. Fig. 6 displays the curve of dynamic viscosity (measured in mPa·s) versus relative viscosity (in seconds), as well as the equation that

can be used to convert relative viscosity (X) to dynamic viscosity (Y). The equation shown in Fig. 6 can be simplified to:

$$Y = 33X^{1/2}.$$

Three-point bending tests and roughness tests results

The flexural strength values of the ceramic samples after drying and firing are presented in Fig. 7. The impact of slurry viscosity and fused silica particle size on the flexural strength was evaluated for each binder. In most cases, the strength of the samples increased with an increase in the slurry viscosity and decrease in FS particle size. Decreasing the size of the FS particles facilitated an increase in the contact area between the stucco particles, thereby improving strength.

Regarding the effects of slurry viscosity, it appears that an increase in viscosity results in a greater amount of binder remaining on the previous layer before the

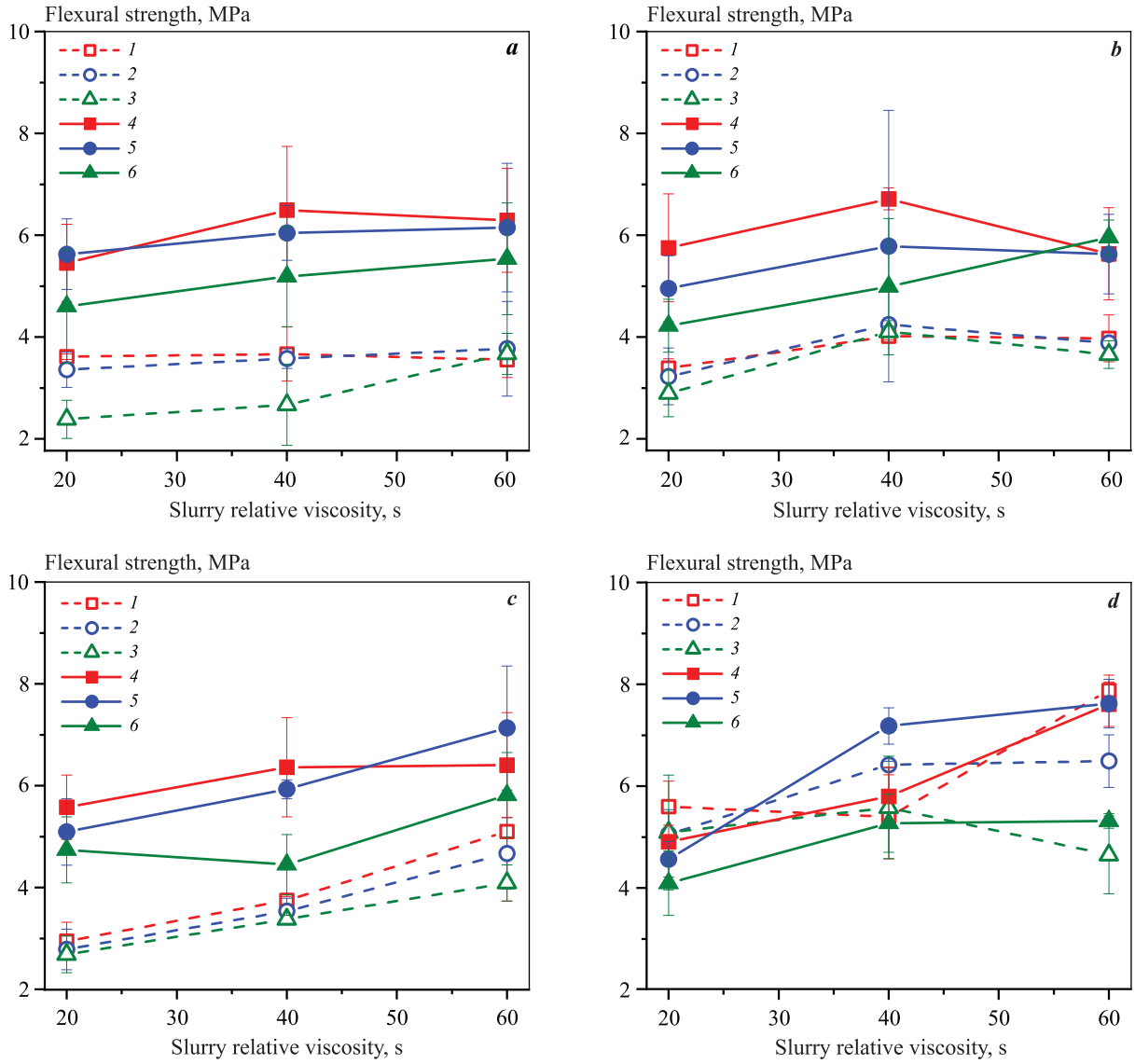

Fig. 7. Flexural strength of ceramic shell specimens obtained with binders: VT13-02U (***a***), Stavroform VS (***b***), UltraCast One+ (***c***), UltraCast Prime (***d***) as dried (***1–3***) and after firing (***4–6***)

Fused silica fraction: FS 0.25–0.4 mm (***1***, ***4***), FS 0.4–0.6 mm (***2***, ***5***), FS 0.5–1.0 mm (***3***, ***6***)

Рис. 7. Прочность на изгиб керамических образов, полученных на связующих ВТ13-02У (***a***), Ставроформ ВС (***b***), UltraCast One+ (***c***), UltraCast Prime (***d***), в состоянии после сушки (***1–3***) и прокалки (***4–6***)

Фракция плавленого кварца: ПК 0,25–0,4 мм (***1***, ***4***), ПК 0,4–0,6 мм (***2***, ***5***), ПК 0,5–1,0 мм (***3***, ***6***)

stucco application. This leads to an increase in the volume fraction of solidified binder relative to the stucco content in the ceramcs. A previous study by authors [29] has also reported an increase in ceramic strength with an increase in slurry viscosity.

Fig. 8 depicts the flexural strength of ceramic samples containing various binders at an slurry viscosity of 40 s and FS 0.4—0.6 mm fused silica grade, after drying and firing. For samples obtained with VT13-02U, Stavroform VS, and UltraCast One+ binders, the flexural strength after drying ranges from 3.5 to 4.3 MPa, and after firing, 5.8 to 6.1 MPa, resulting in a 1.5x increase due to ceramic firing. Typically, the strength of "green" ceramics is approximately half of that after firing [17, 18, 25], which is consistent with our results and those reported in previous studies [10, 17, 24].

It is noteworthy that the strength before firing is primarily determined by the wax penetration into small defects and pores as wax is not entirely removed by dewaxing in boiling water [30]. We used the paraffin/stearin 50/50 wax; high strength filled waxes may result in higher strength of the green sample.

The properties of ceramics made with the UltraCast Prime binder are slightly different. The strengths after drying and firing are 6.4 and 7.2 MPa, respectively, which is higher both before and after firing in comparison to ceramics made with other binders. Previous studies [26] suggest that adding a polymer to the binder results in higher flexural strength of the "green" ceramics equivalent of that of the fired sample. The higher strength of the ceramics containing the UltraCast Prime binder is attributed to the addition of a polymer into binder to increase the strength before firing.

The most common flexural strength values for ceramic molds are 3—10 MPa [10, 17, 24, 31]. The tested binders generally provide the required strength values for ceramic molds even before firing, with the exception of slurries with low relative viscosity (~20 s) and coarse fused silica stucco (FS 0.5—1.0 mm).

Increasing the mold firing temperature can result in the formation of cristobalite [14], which may increase the strength of the ceramics but also increase the thermal expansion coefficient, making it undesirable [14]. Another method to increase the strength of ceramics (from 15 to 40 MPa) is by adding alumina powder as a filler to the slurry, along with alumina refractory as the stucco [9].

In terms of surface roughness the ceramic samples obtained with the VT13-02U and Stavroform binders exhibited similar values, with R_z = 25 ± 2 and 26 ± 3 μm, respectively, falling within the confidence interval. The ceramic samples obtained using the UltraCast Prime and UltraCast One+ binders dispayed lower R_z values: 15 ± 1 and 21 ± 2 μm, respectively.

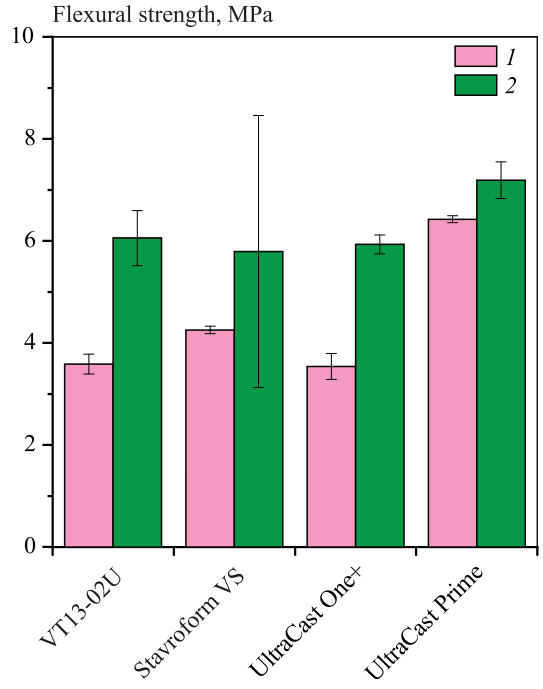

Fig. 8. The flexural strength of ceramic shell samples obtained with various binders after drying (***1***) and firing (***2***) at a slurry viscosity of 40 s and a fused silica fraction FS 0.4—0.6 mm

Рис. 8. Прочность на изгиб керамических образов, полученных на различных связующих, в состояниях после сушки (***1***) и прокалки (***2***) при вязкости суспензии 40 с и фракции плавленого кварца ПК 0,4—0,6 мм

The domestic colloidal silica binders exhibit similar properties to hydrolyzed ethyl silicate binders, but with the added benefits of being non-flammable and environmentally friendly [5, 7—9, 12]. This enables their use in the production of ceramic shells for making castings on automated and robotic lines, after correction of technological parameters, which are selected for each binder separately.

Conclusion

The study focused on the viscosity of the slurries made with colloidal silica binders (VT13-02U, Stavroform VS, UltraCast One+, and UltraCast Prime) and fused silica powder, as well as on the flexural strength of the ceramic samples produced from these

slurries with fused silica stucco. The results are as follows.

1. The slurries are close to Newtonian fluids with similar viscosities. Specifically, at binder contents of 400 and 600 mL per 1 kg of fused silica powder, the average dynamic viscosity is ~732 and ~70 mPa·s, respectively.

2. The increase the binder content from 400 to 600 mL per 1 kg of fused silica powder results in a significant decrease in relative viscosity from ~380 to ~16 s, respectively (up to 24 times). The relationship between the relative (X) and dynamic (Y) viscosities can be expressed by the following equation: $Y = 33X^{1/2}$.

3. The flexural strengths of the samples which contain the binders VT13-02U, Stavroform VS, and UltraCast One+ are similar, with values ranging from 3.5 to 4.3 MPa after drying and 5.8 to 6.1 MPa after firing. For the UltraCast Prime binder, the flexural strengths after drying and firing are 6.4 and 7.2 MPa, respectively. The high strength observed in "green" state of the UltraCast Prime binder may be due to the presence of polymer additives in the binder.

4. The strength of the samples, both after drying and firing, increases with increasing slurry viscosity and decreasing fused silica stucco particle size.

5. The surface roughness of the ceramic samples containing the VT13-02U and Stavroform binders was found to be $R_z = 25 \pm 2$ and 26 ± 3 μm, respectively. In contrast, the ceramic samples made with the UltraCast Prime and UltraCast One+ binders exhibited lower surface roughness values of 15 ± 1 and 21 ± 2 μm, respectively.

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A.V. Koltygin – scientific guidance, review and editing of the manuscript.

D.V. Ten – realization of experiment, analysis of the experimental results.

A.A. Rizhsky – realization of experiment, analysis of the experimental results.

V.D. Belov – supervision, review and editing of the manuscript.

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