

ORIGINAL STUDY

EFFECT OF COMPOSITION AND CONSOLIDATION METHOD ON THE MICROSTRUCTURE, HARDNESS, AND TRIBOLOGICAL PROPERTIES OF SiO₂–NiCr COMPOSITE PELLETS PRODUCED BY SPARK PLASMA SINTERING AND HOT PRESSINGSerikkhan Almira^{1*}, Kenesbekov Aidar¹, Kussainov Temirlan¹¹Institute of Composite Materials LLP, Ust-Kamenogorsk, Kazakhstan*Corresponding author: almiraserikkhan@mail.ru

Abstract. *This study investigated the effects of the SiO₂–NiCr composition and thermomechanical consolidation method on the microstructure, phase composition, mechanical properties, and tribological behavior of composites produced by spark plasma sintering (SPS) and hot pressing. The samples were characterized by X-ray diffraction, scanning electron microscopy, energy-dispersive X-ray spectroscopy, X-ray fluorescence analysis, Vickers hardness measurements, and tribological testing. The composites exhibited a heterogeneous cermet structure, with Ni and Cr distributed in the metallic constituent and SiO₂ forming the oxide phase. The maximum Vickers hardness, 2020.2 ± 165.9 HV, was recorded for the hot-pressed sample with an SiO₂/NiCr ratio of 70/30. The minimum mean coefficient of friction (0.135) was obtained for the SPS-produced sample with a 50/50 composition. The results demonstrate that both composition and consolidation method substantially affect the microstructure, phase composition, hardness, and tribological properties of SiO₂–NiCr composites.*

Keywords: spark plasma sintering, hot pressing, SiO₂–NiCr, cermet composite, microstructure, phase composition, hardness, coefficient of friction.

1. Introduction

In powder metallurgy, spark plasma sintering (SPS) and hot pressing are among the most effective methods for consolidating powder materials under uniaxial pressure at elevated temperature; however, they differ in the mode of heat supply and the thermomechanical processing conditions. During SPS, heating is generated by a pulsed electric current passing through the graphite tooling and, depending on the electrical conductivity of the material, through the powder compact. This provides a high heating rate, short holding time, and limited grain growth [1–4]. For dielectric SiO₂, consolidation efficiency is governed by heat-transfer conditions and the temperature–time regime [5], whereas temperature and pressure are the key factors controlling the density, grain size, and mechanical properties of nickel-based materials [6]. Unlike SPS, hot pressing consolidates the powder mixture by external heating. The feasibility of producing bulk Ni–SiO₂ composites by this method has been demonstrated previously [7, 8].

Published data indicate that consolidation parameters, including temperature, pressure, heating rate, and holding time, determine densification kinetics, microstructure formation, and phase retention [1–6]. Therefore, both the nominal composition and the consolidation method must be considered when examining the structure and functional properties of SiO₂–NiCr composites.

Studies of bulk SiO₂–NiCr composites produced by SPS and hot pressing remain scarce. The most closely related investigations concern Ni–SiO₂ composites prepared by mechanical milling [9], sol–gel processing [10, 11], spray pyrolysis [12], and hot pressing [7, 8, 18]. These studies show that composite composition, consolidation conditions, and heat treatment determine the degree of densification, metallic-particle size, particle distribution in the silica matrix, and phase state of the material [7–13]. Hot pressing may also produce a transition layer at the Ni/SiO₂ interface, indicating interfacial interaction at elevated temperatures [8].

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Studies of Ni–SiO₂ composites show that increasing the metallic fraction changes the size and spatial distribution of Ni particles [9, 10, 12–14], whereas a more uniform distribution of SiO₂ can improve the microhardness and wear resistance of the material [15–17]. These relationships cannot be transferred directly to the SiO₂–NiCr system because Cr affects consolidation, microstructure formation, and the resulting functional properties.

Despite extensive research on Ni–SiO₂ composites, little information is available on the influence of composition and consolidation method on the microstructure, phase composition, mechanical properties, and tribological behavior of bulk SiO₂–NiCr composites. The aim of this study was therefore to determine how the nominal SiO₂/NiCr ratio and consolidation method—spark plasma sintering or hot pressing—affect the microstructure, phase composition, mechanical properties, and tribological behavior of the resulting composites.

2. Materials and Methods

SiO₂–NiCr composite samples were prepared from powder mixtures with nominal component ratios of 30/70, 50/50, and 70/30. Two series were produced for each composition: series M by spark plasma sintering (SPS) and series L by hot pressing (HP). Series M samples were consolidated in a graphite die under the simultaneous action of uniaxial pressure and a pulsed electric current. Series L samples were produced by hot pressing under elevated temperature and uniaxial pressure with external heat supply. The SPS and hot-pressing parameters, including temperature, pressure, heating rate, holding time, and processing atmosphere, are listed in Table 1.

Table 1. Processing conditions for the SiO₂–NiCr composite samples.

Sample	SiO ₂ /NiCr, wt.%	Method	Temperature, °C	Pressure, MPa	Heating rate, °C/min	Holding time, min	Atmosphere
M-1	30/70	SPS	1000	50	100	10	Vacuum
M-2	50/50						
M-3	70/30						
L-1	30/70	HP	1100	30	10	60	
L-2	50/50						
L-3	70/30						

The surface microstructure and morphology of the samples were examined by scanning electron microscopy (SEM) using a TESCAN VEGA4 LMH microscope (TESCAN, Brno, Czech Republic). Energy-dispersive X-ray spectroscopy (EDS) was performed using an Xplore 30 system (Oxford Instruments, Oxford, United Kingdom). X-ray diffraction (XRD) analysis was conducted on a DX-27mini diffractometer (Dandong Haoyuan Instrument Co., Ltd., China) using Cu K α radiation ($\lambda = 0.154$ nm) at an operating voltage of 40 kV and a current of 30 mA. Measurements were collected over a 2θ range of 20–90°, with a step size of 0.05° and a counting time of 3 s per step. Phase identification was performed using HighScore software, version 4. The elemental composition was examined by X-ray fluorescence (XRF) analysis using an X-MET 8000 SMART portable analyzer. The Vickers hardness of the composite samples was measured using a FISCHERSCOPE HM2000 measurement system (Helmut Fischer GmbH, Germany). The indenter approach rate was 2 μ m/s, and the applied-load range was 0.1–2000 mN. Tribological tests were conducted on an Anton Paar TRB3 tribometer (Anton Paar, Buchs, Switzerland) in a ball-on-disc configuration in accordance with ASTM G133-95 and ASTM G99. Tests were performed under dry sliding conditions using a 6 mm diameter 100Cr6 steel ball as the counterbody. The normal load was 1 N, the linear sliding speed was 5 cm/s, and the wear-track radius was 4 mm, corresponding to a rotational speed of approximately 119 rpm.

3. Results and Discussion

3.1. Microstructure and Elemental Distribution

SEM images of the investigated pellets are presented in [Figs. 1](#) and [2](#). The surfaces of all samples exhibit heterogeneous contrast characteristic of combined metallic and oxide regions. The 50/50 compositions show a predominantly fine-grained surface relief, whereas the 70/30 pellets exhibit more pronounced height variations and local heterogeneity. A relationship between microstructure and the distribution of the metallic constituent within a silica medium has previously been reported for Ni–SiO₂ materials [\[6\]](#).

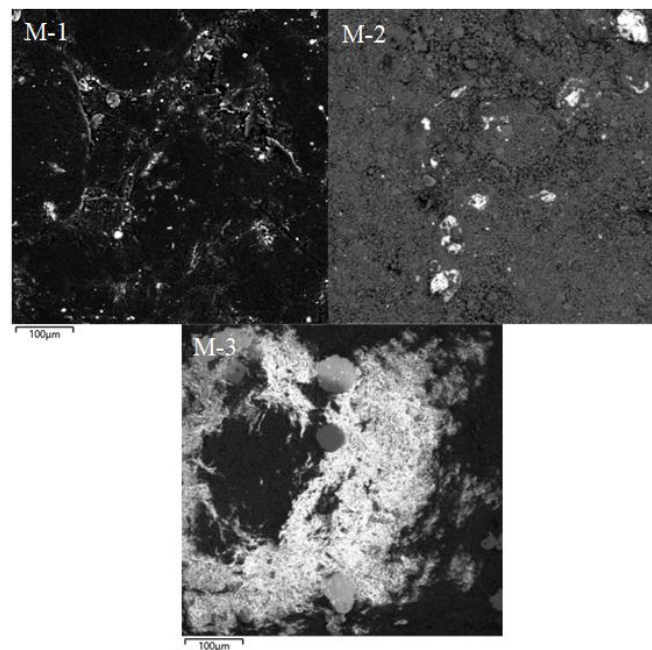


Fig. 1. SEM images of the surfaces of the series M SiO₂–NiCr composite pellets: M-1 (30/70), M-2 (50/50), and M-3 (70/30).

Sample M-1 (30/70) has a relatively dense and uniform surface. Local bright inclusions and minor surface irregularities are visible in some regions, but no pronounced network of large pores or extended cracks is observed. Smoother areas coexist with regions of increased roughness, indicating a certain degree of microstructural heterogeneity. The surface of M-2 (50/50) is more heterogeneous. The micrographs show numerous depressions, microdefects, and regions with different contrast. In some areas, the surface has a fine, granular morphology. Local cavities and discontinuities may indicate lower structural uniformity than in M-1. The most developed surface relief is observed for M-3 (70/30). Its surface contains pronounced irregularities, local protrusions and depressions, and regions with complex morphology. Some areas are markedly rougher, whereas others appear relatively smooth. This combination of distinct morphological regions indicates heterogeneous structure formation at this component ratio. Overall, the SEM observations show that changing the composition from 30/70 to 70/30 substantially affects surface morphology. Sample M-1 has a comparatively uniform and compact structure, whereas M-2 and particularly M-3 show increasingly pronounced surface relief and structural heterogeneity.

SEM images of the series L samples are presented in [Fig. 2](#) and reveal clear differences in surface morphology.

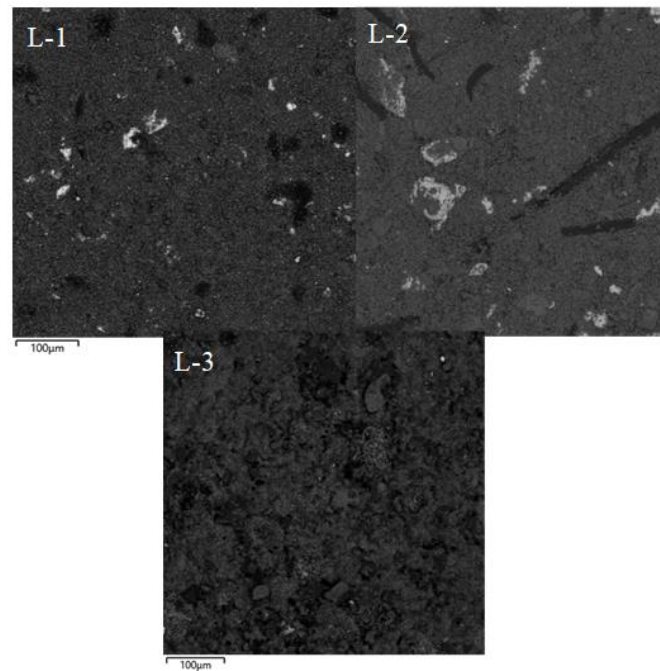


Fig. 2. SEM images of the series L SiO_2 –NiCr composite pellets: L-1 (30/70), L-2 (50/50), and L-3 (70/30).

Sample L-1 contains relatively smooth regions separated by extended crack-like defects and local depressions. Isolated protrusions and fine particles are also visible. These features are distributed nonuniformly: flat regions coexist with areas of pronounced relief. Sample L-2 has a finer, network-like surface texture. Against this background, individual rounded depressions and elongated dark bands are visible, corresponding to discontinuities or abrupt changes in topography. Local bright regions with irregular shapes are also distributed nonuniformly across the examined area. The surface of L-3 exhibits the most developed relief, consisting of tortuous ridges, protrusions, and numerous depressions of different shapes. Compared with L-1 and L-2, large smooth regions are less evident, and morphological heterogeneity extends over most of the field of view.

The differences between series M and L may be associated with their distinct heating modes - rapid current-assisted heating during SPS and external heating during hot pressing - as well as with differences in holding time and degree of densification. Thus, the L-1 to L-3 sequence shows a transition from a surface containing relatively smooth regions to a more complex and pronounced relief. The images permit a qualitative comparison of sample morphology; quantitative determination of roughness and porosity requires additional measurements. Elemental analysis is necessary to identify the chemical nature of regions with different brightness.

The EDS results must therefore be considered to identify the bright and dark regions and determine their chemical nature, because SEM contrast alone does not provide unambiguous phase or elemental identification. [Figures 3](#) and [4](#) present elemental distribution maps for the SiO_2 –NiCr pellets.

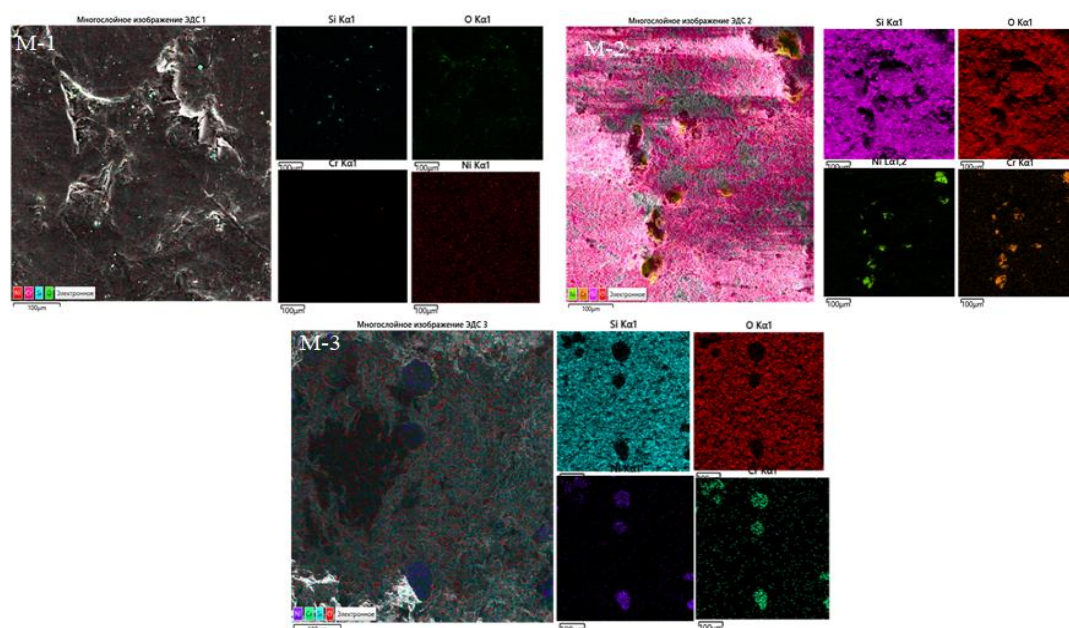


Fig. 3. EDS elemental maps of the series M SiO₂–NiCr composite pellets: M-1 (30/70), M-2 (50/50), and M-3 (70/30)

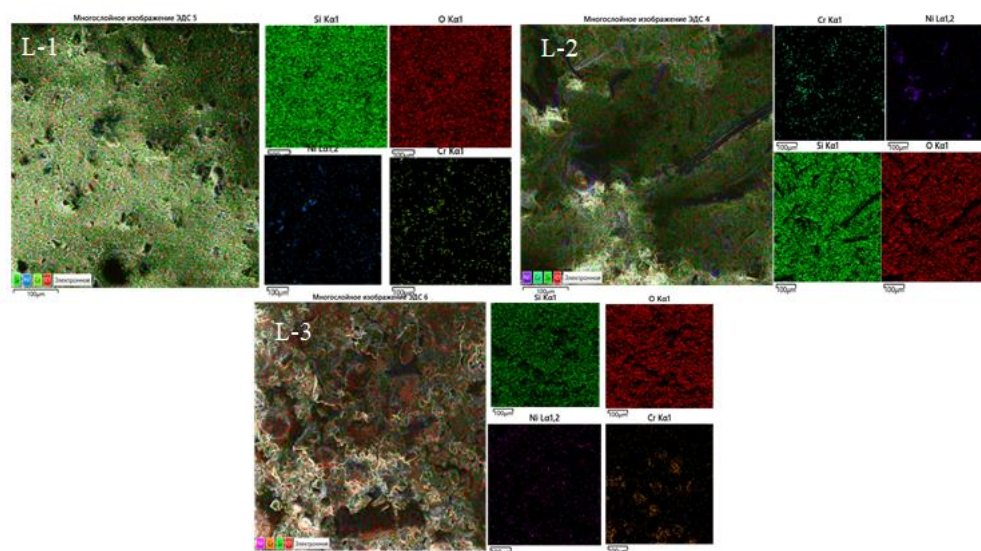


Fig. 4. EDS elemental maps of the series L SiO₂–NiCr composite pellets: L-1 (30/70), L-2 (50/50), and L-3 (70/30).

EDS mapping of the SiO₂–NiCr composite pellet surfaces revealed a heterogeneous but spatially correlated distribution of the principal elements. Si and O signals occur across nearly the entire examined area, indicating the formation of a continuous SiO₂-containing matrix. Regions of increased Si and O intensity largely coincide, confirming their joint presence in the oxide constituent. In the series M samples, Ni and Cr are distributed mainly as isolated local regions and finely dispersed inclusions. M-1 exhibits the most heterogeneous distribution of Si and O, together with individual regions enriched in NiCr constituents. In M-2, the Si-O-containing phase is distributed more uniformly, whereas Ni and Cr are concentrated primarily in individual particles and agglomerates. M-3 retains a continuous Si and O distribution but also contains local regions jointly enriched in Ni and Cr, indicating that discrete NiCr-alloy particles remain within the oxide matrix. The series L samples likewise contain a predominantly uniform SiO₂-bearing phase. In L-1, Si and O signals cover most of the surface, while Ni and Cr occur as dispersed inclusions. L-2 has a comparatively homogeneous Si-O matrix with local accumulations of metallic constituents. L-3 exhibits developed heterogeneous relief and individual agglomerates; Si and O are distributed across the entire examined area, whereas Ni and Cr are localized primarily in discrete regions. Overall, increasing the SiO₂

fraction from 30 to 70% produces a more pronounced continuous oxide matrix, while Ni- and Cr-rich regions become more localized. The partial spatial coincidence of Ni and Cr signals indicates that particles of the initial NiCr alloy persist after mixing and pressing. Local regions with elevated metallic-element concentrations indicate incomplete homogenization of the powder mixture and possible agglomeration. EDS maps provide mainly qualitative information on elemental distribution; quantitative comparison requires analysis of the corresponding EDS spectra. [Table 2](#) presents the XRF results, which describe the relative proportions of the elements detected by this method. Ni is the dominant element in every composition, and Cr is the second major metallic constituent. The elevated W content in the 70/30 sample and trace amounts of Sn, Ti, Pd, Cu, Zn, Nb, Mo, Au, and Zr may reflect the composition of the initial NiCr powder, processing-related contamination, or calibration effects. Because Si and O were not quantified by XRF in this series, [Table 2](#) does not represent a complete mass balance and should be interpreted together with the EDS and XRD results.

Table 2. Relative elemental composition of the samples determined by XRF analysis, wt.%.

Sample	Ni	Cr	W	Fe	Sn	Ti	Pd	Cu	Zn	Nb	Mo	Au	Zr	Pb
M-1	83.61	15.37	0.07	0.49	–	0.10	0.06	0.06	0.03	–	0.03	–	–	–
M-2	80.84	13.31	3.44	1.08	0.73	0.22	0.06	0.05	0.03	0.02	0.01	–	–	–
M-3	70.94	13.80	9.70	1.51	1.82	0.91	0.22	0.01	0.03	–	0.02	0.68	0.11	–
L-1	80.38	14.54	0.60	3.57	0.23	0.16	–	0.05	0.01	–	0.17	–	–	–
L-2	82.16	13.18	1.78	1.85	0.48	0.10	–	0.06	–	0.01	0.04	–	–	–
L-3	69.90	16.36	2.68	3.27	1.36	0.19	–	0.05	0.07	0.02	0.05	0.16	0.03	4.87

3.2. Phase Composition

The XRD patterns of series M and L are presented in [Figs. 5](#) and [6](#). All patterns contain intense reflections provisionally assigned to a Ni-containing metallic phase, together with reflections from Cr- and SiO₂-containing constituents. Changes in relative peak intensity reflect the effects of nominal composition, local heterogeneity, and processing method; however, they cannot be used to quantify phase fractions without Rietveld refinement. The phase state of both series may have changed under the applied temperature and pressure, while differences between series M and L may result from the mode of heat supply, heating rate, and holding time during SPS and hot pressing.

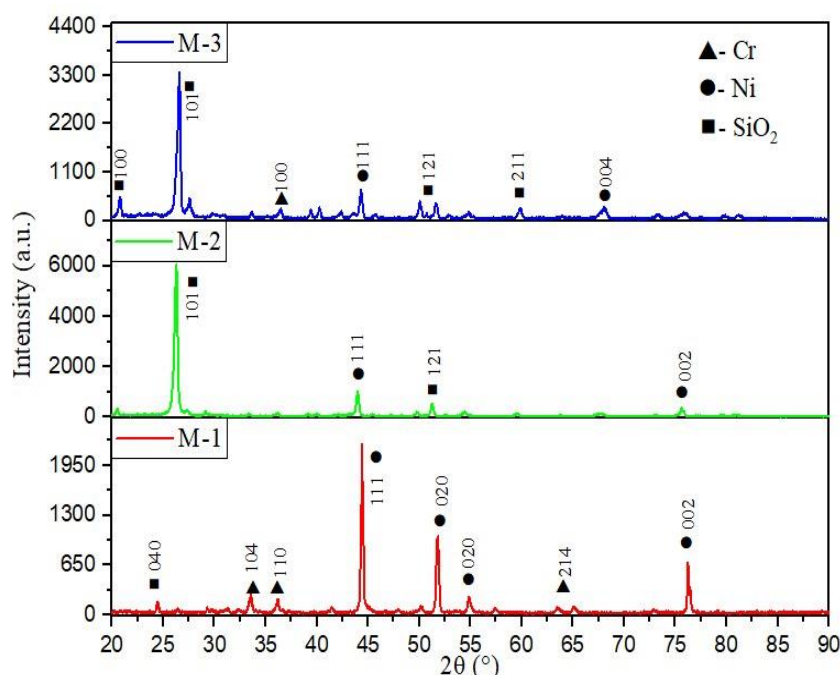


Fig. 5. XRD patterns of the SiO₂-NiCr composite samples produced by spark plasma sintering (SPS): M-1 (30/70), M-2 (50/50), and M-3 (70/30).

Figure 5 presents the XRD patterns of the series M samples produced by spark plasma sintering. For M-1 (30/70), the most intense diffraction maximum occurs at $2\theta \approx 44\text{--}45^\circ$ and corresponds to the Ni(111) reflection identified in the figure. Additional Ni reflections occur at approximately 52° , 55° , and $75\text{--}76^\circ$, whereas less intense Cr peaks are observed near $33\text{--}37^\circ$ and $63\text{--}65^\circ$. The SiO₂ reflection is substantially weaker, consistent with the greater proportion of the metallic NiCr constituent in this composition. The diffraction pattern changes markedly for M-2 (50/50). The intense SiO₂(101) reflection at $2\theta \approx 26\text{--}27^\circ$ becomes dominant. The Ni(111) reflection near $44\text{--}45^\circ$ and an additional Ni-containing maximum near $75\text{--}76^\circ$ are retained. The stronger SiO₂ peak relative to M-1 reflects the increased oxide fraction. For M-3 (70/30), the SiO₂(101) reflection at $26\text{--}27^\circ$ is again the most intense. Additional SiO₂ peaks are present at approximately $20\text{--}21^\circ$, $50\text{--}52^\circ$, and $59\text{--}60^\circ$, while the metallic Ni and Cr reflections have lower relative intensities. Thus, increasing the SiO₂ content from 30 to 70 wt.% in the SPS series changes the diffraction pattern from one dominated by Ni-Cr to one dominated by SiO₂.

Figure 6 presents the XRD patterns of the series L samples produced by hot pressing.

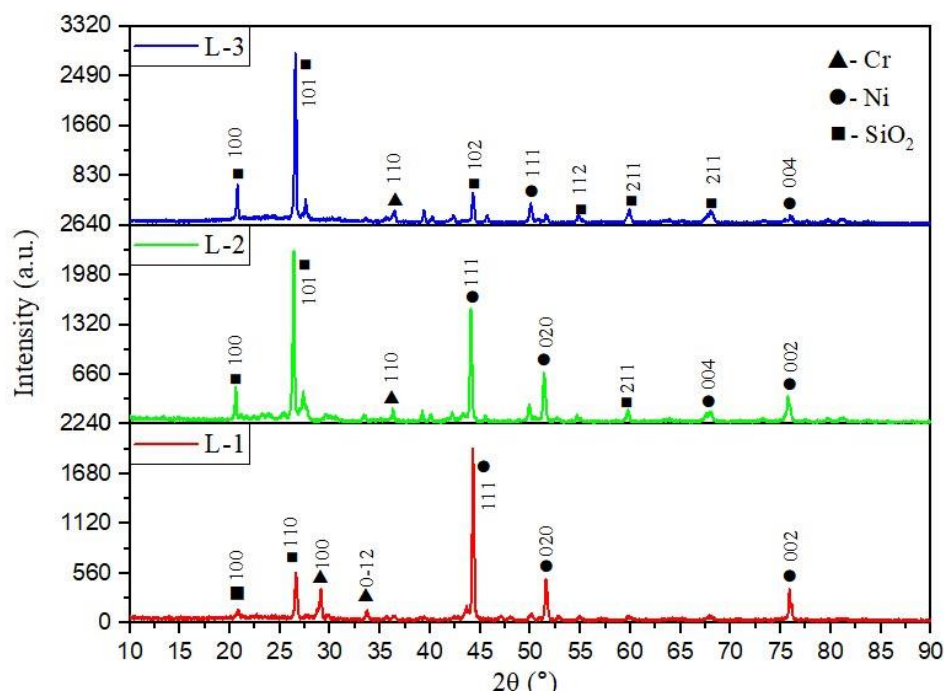


Fig. 6. XRD patterns of the SiO₂-NiCr composite samples produced by hot pressing (HP): L-1 (30/70), L-2 (50/50), and L-3 (70/30).

[Figure 6](#) presents the XRD patterns of the series L samples produced by hot pressing at different SiO₂/NiCr ratios. The diffraction pattern of L-1 (30/70) is dominated by reflections from the metallic constituent. The most intense maximum occurs at $2\theta \approx 44\text{--}45^\circ$ and, according to the indexing shown in the figure, corresponds to Ni(111). Additional Ni-containing reflections occur at approximately $51\text{--}52^\circ$ and $75\text{--}76^\circ$, while less intense reflections assigned to Cr and SiO₂ appear at approximately $26\text{--}36^\circ$. For L-2 (50/50), the intensity of the SiO₂ reflection at $2\theta \approx 26\text{--}27^\circ$, indexed as SiO₂(101), increases substantially. The pronounced Ni(111) peak near $44\text{--}45^\circ$ and additional metallic reflections at higher angles remain visible. Thus, both oxide and metallic constituents are evident in the diffraction pattern of the equiatomic SiO₂/NiCr composition. For L-3 (70/30), the SiO₂(101) maximum near $26\text{--}27^\circ$ becomes dominant. Additional SiO₂ reflections occur at approximately $20\text{--}21^\circ$, $39\text{--}40^\circ$, and $50\text{--}60^\circ$, whereas the relative intensities of the Ni and Cr reflections decrease. Overall, increasing the SiO₂ content from 30 to 70 wt.% systematically strengthens its diffraction reflections and reduces the relative contribution of the metallic Ni-Cr constituent.

3.3. Mechanical Properties

[Figure 7](#) presents the instrumented indentation loading-unloading curves for the series M samples with different component ratios: M-1 (30/70), M-2 (50/50), and M-3 (70/30). At the same maximum load, the curve shape and indentation depth differ substantially, indicating differences in resistance to local deformation.

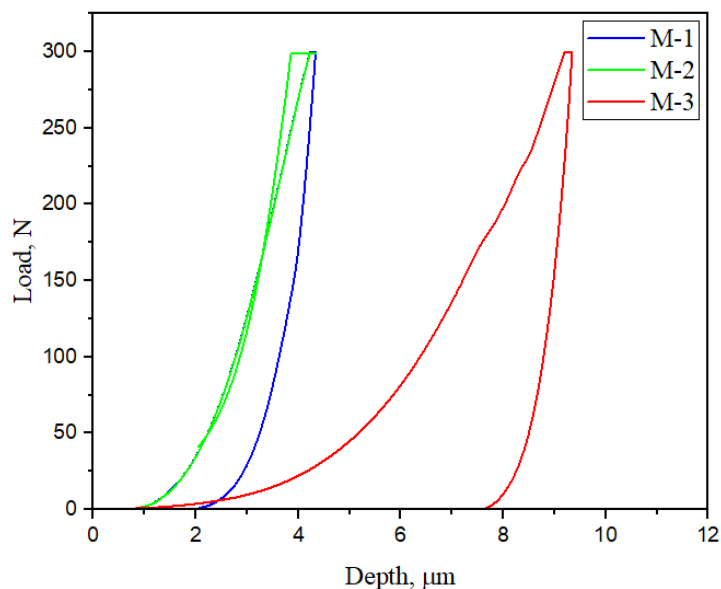


Fig. 7. Instrumented indentation loading–unloading curves for the series M samples: M-1 (30/70), M-2 (50/50), and M-3 (70/30).

The maximum indentation depth is approximately 4.1 μm for M-2 (50/50) and is slightly greater, approximately 4.3–4.4 μm , for M-1 (30/70). The close positions of the M-1 and M-2 curves indicate comparable indentation resistance, although M-2 shows a slightly smaller penetration depth.

The most pronounced deformation is observed for M-3 (70/30), for which the maximum indentation depth reaches approximately 9.2–9.4 μm . The marked shift of the M-3 curve toward greater depths indicates lower resistance to local deformation and a larger plastic contribution. Based on the loading–unloading curves, indentation resistance in series M decreases in the following order: M-2 (50/50) > M-1 (30/70) >> M-3 (70/30).

[Figure 8](#) presents the instrumented indentation loading–unloading curves for the series L samples with different component ratios: L-1 (30/70), L-2 (50/50), and L-3 (70/30). The curves demonstrate a pronounced effect of composition on indentation depth and the elastic–plastic response of the material.

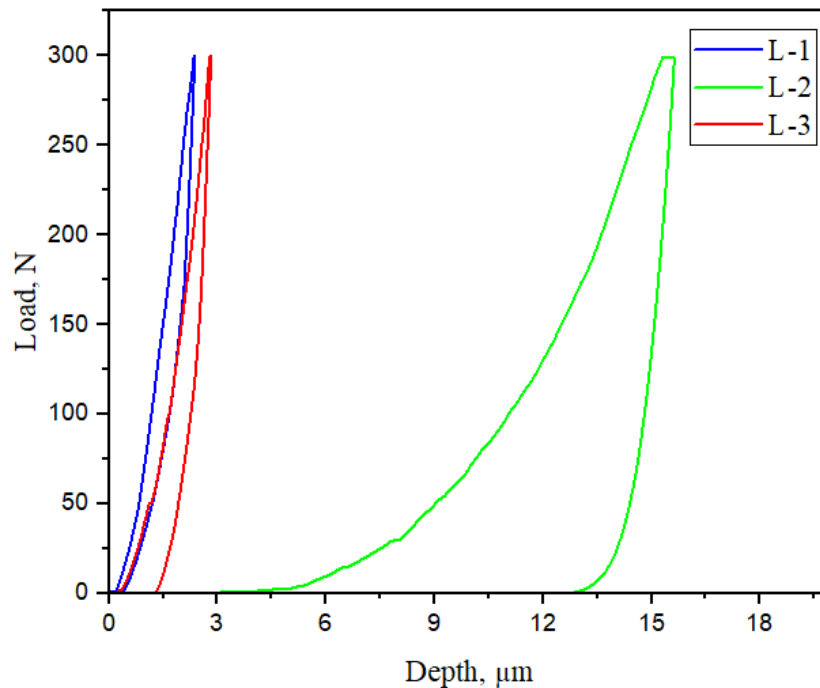


Fig. 8. Instrumented indentation loading–unloading curves for the series L samples: L-1 (30/70), L-2 (50/50), and L-3 (70/30).

The lowest maximum indentation depth, approximately 2.3–2.4 μm , is observed for L-1 (30/70). For L-3 (70/30), the depth is slightly greater at approximately 2.8–2.9 μm , indicating somewhat lower resistance to local deformation than L-1. The greatest increase in indentation depth occurs for L-2 (50/50). At the maximum load, the indentation depth reaches approximately 15–16 μm , considerably exceeding the values for L-1 and L-3. This behavior indicates substantially greater deformability and lower resistance to local indentation in L-2. Accordingly, indentation resistance in series L decreases in the following order: L-1 (30/70) > L-3 (70/30) >> L-2 (50/50).

Comparative analysis of the instrumented indentation results ([Table 3](#)) shows that the mechanical properties of the SiO_2 –NiCr composites vary nonmonotonically with composition and consolidation conditions.

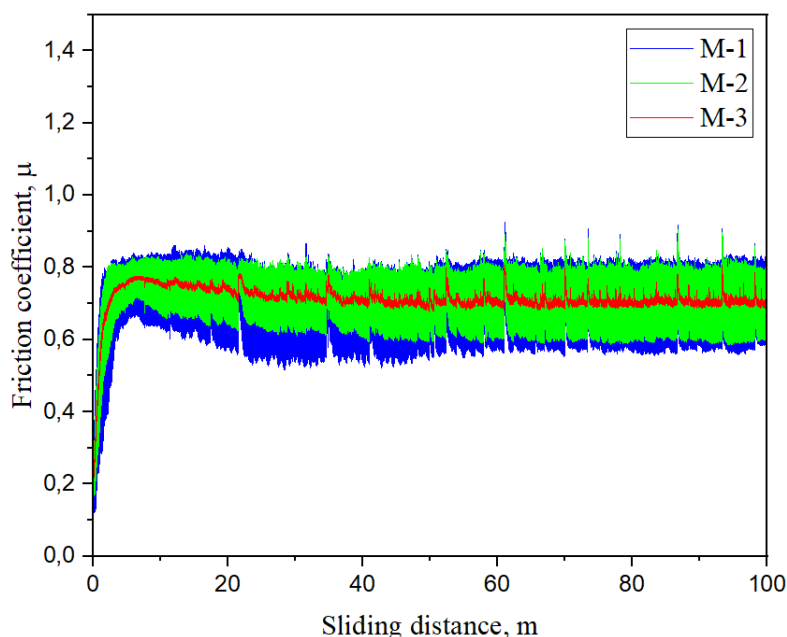
Table 3. Mechanical properties of the series M and L samples.

Sample	HM, N/mm ²	HV	E, GPa
M-1	663.3 ± 231.8	93.8 ± 36.0	19.3 ± 6.4
M-2	131.6 ± 10.7	15.6 ± 1.3	8.9 ± 2.5
M-3	525.7 ± 75.9	73.7 ± 12.1	17.0 ± 2.8
L-1	2020.2 ± 165.9	361.0 ± 52.9	43.3 ± 3.9
L-2	47.5 ± 2.2	5.5 ± 0.3	3.6 ± 1.1
L-3	1550.4 ± 566.0	235.0 ± 87.8	42.3 ± 16.0

The highest mean values were obtained for L-1 (30/70): the Vickers hardness was 361.0 ± 52.9 HV, the Martens hardness was 2020.2 ± 165.9 N/mm², and the indentation modulus was 43.3 ± 3.9 GPa. The lowest values were recorded for L-2 (50/50): 5.5 ± 0.3 HV, 47.5 ± 2.2 N/mm², and 3.6 ± 1.1 GPa, respectively. Based on mean hardness, the samples follow the sequences M-1 > M-3 > M-2 and L-1 > L-3 > L-2. At SiO₂/NiCr ratios of 30/70 and 70/30, the series L samples exhibit higher hardness and indentation modulus than the corresponding series M samples, whereas the opposite relationship is observed for the 50/50 composition. The relative advantage of each consolidation method therefore depends on the component ratio. Among the investigated samples, L-1 combines the 30/70 composition and hot-pressing conditions to provide the highest mean hardness and indentation modulus.

3.4. Tribological Behavior

Figures 9 and 10 show the coefficient of friction as a function of sliding distance for the series M and L samples with different component ratios: M-1 and L-1, 30/70; M-2 and L-2, 50/50; and M-3 and L-3, 70/30. In every case, the initial portion of the test corresponds to a running-in stage with a rapid change in the coefficient of friction, followed by steady-state or quasi-steady-state sliding.

**Fig. 9.** Coefficient of friction as a function of sliding distance for M-1 (30/70), M-2 (50/50), and M-3 (70/30).

The series M samples enter the quasi-steady-state regime comparatively rapidly. After the initial increase, the coefficient of friction of M-1 (30/70) varies mainly within approximately 0.58–0.83, with noticeable high-frequency fluctuations persisting throughout the test. M-2 (50/50) exhibits a similar friction level; after running-in, the values generally remain near 0.62–0.78. M-3 (70/30) produces a smoother curve: after the initial stage, the coefficient of friction stabilizes mainly within approximately 0.69–0.75 and then changes only slightly up to a sliding distance of 100 m. Thus, the component ratio in series M affects both the magnitude of the coefficient of friction and the stability of the frictional contact. Within this series, M-3 exhibits the smoothest tribological curve and the smallest fluctuation amplitude.

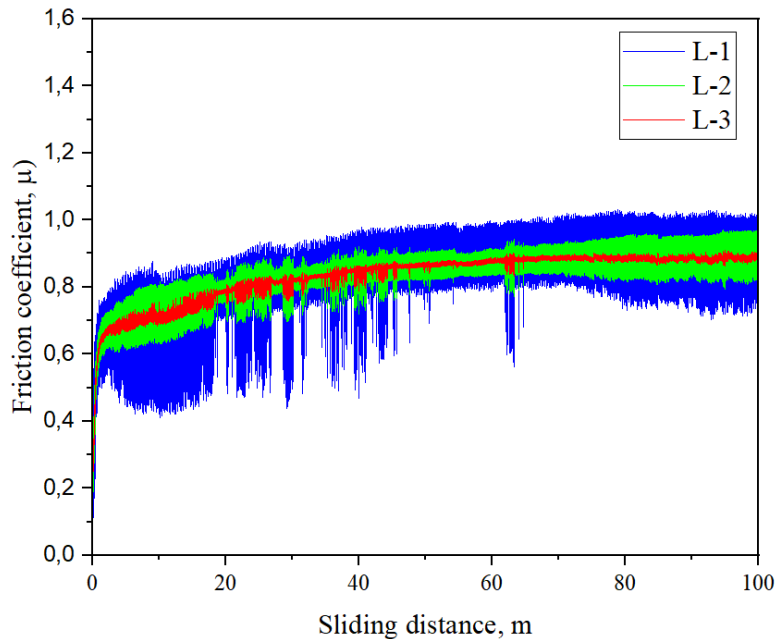


Fig. 10. Coefficient of friction as a function of sliding distance for L-1 (30/70), L-2 (50/50), and L-3 (70/30).

The coefficient of friction follows a different evolution in series L. After the initial running-in stage, it does not immediately reach a constant level but continues to increase gradually with sliding distance. L-1 (30/70) exhibits the largest signal fluctuations. Sharp, short-term decreases in the coefficient of friction occur in several regions, particularly between approximately 15 and 45 m, while the upper level of the curve approaches 1.0 by the end of the test. These fluctuations indicate unstable frictional-contact conditions and possible periodic changes in the state of the contacting surfaces during sliding. L-2 (50/50) exhibits a more uniform increase in the coefficient of friction. After an initial rise to approximately 0.65–0.70, the value increases gradually and reaches approximately 0.90–0.96 in the final part of the test. The fluctuations are less pronounced than for L-1, although the coefficient of friction continues to increase throughout the investigated sliding distance. L-3 (70/30) exhibits the most stable behavior within series L. After a short running-in period, the coefficient of friction rises smoothly from approximately 0.65–0.70 to 0.87–0.90 and then changes only slightly. Compared with L-1 and L-2, the L-3 curve has a smaller fluctuation amplitude, indicating a more stable friction process.

Comparison of series M and L shows that the series M samples generally enter the quasi-steady-state friction regime more rapidly, whereas series L exhibits a longer period of gradual increase in the coefficient of friction. In both series, the 70/30 compositions (M-3 and L-3) produce the smoothest tribological curves. The presented dependences support conclusions primarily about the magnitude and stability of the coefficient of friction. A quantitative assessment of wear resistance additionally requires the wear volume or wear rate, wear-track profile, and post-test surface morphology.

4. Conclusions

A comparative investigation was conducted to determine the effects of the SiO₂/NiCr ratio and consolidation method on the structure, mechanical properties, and tribological behavior of the composite pellets. The following conclusions were drawn.

1. The samples produced by spark plasma sintering and hot pressing exhibit a heterogeneous cermet structure. Si and O are distributed over most of the examined surface and form a SiO₂-containing matrix, whereas Ni and Cr are localized mainly in discrete particles and agglomerates. As the SiO₂ fraction increases from 30 to 70 wt.%, the oxide matrix becomes more pronounced and the metallic constituent becomes more localized.

2. According to the XRD results, reflections from the Ni–Cr-containing constituent dominate the diffraction patterns at an SiO₂/NiCr ratio of 30/70. Increasing the SiO₂ content to 50 and 70 wt.% strengthens the SiO₂(101) reflection at $2\theta \approx 26\text{--}27^\circ$ and decreases the relative intensity of the metallic reflections. This trend is observed in both sample series, irrespective of the consolidation method.

3. The mechanical properties vary nonmonotonically and are governed by the combined effects of composition and processing method. The highest values were obtained for hot-pressed L-1 with a 30/70 composition: the Vickers hardness was 361.0 ± 52.9 HV, the Martens hardness was 2020.2 ± 165.9 N/mm², and the indentation modulus was 43.3 ± 3.9 GPa. The lowest values were recorded for L-2 with a 50/50 composition: 5.5 ± 0.3 HV, 47.5 ± 2.2 N/mm², and 3.6 ± 1.1 GPa, respectively. Hot pressing produced higher mechanical properties for the 30/70 and 70/30 compositions, whereas SPS produced higher values for the 50/50 composition.

4. Tribological testing showed that the series M samples enter the quasi-steady-state friction regime more rapidly and generally exhibit lower coefficients of friction than the series L samples. The hot-pressed samples show a gradual increase in the coefficient of friction with sliding distance. The most stable tribological curves in both series were obtained for the 70/30 compositions, M-3 and L-3. Conclusions regarding wear resistance require additional measurements of wear volume or wear rate and analysis of wear-track morphology.

5. The optimum composition and consolidation method therefore depend on the required functional properties. The combination of an SiO₂/NiCr ratio of 30/70 and hot pressing provides the highest hardness and indentation modulus, whereas increasing the SiO₂ content to 70 wt.% promotes more stable friction behavior. These results demonstrate that the structure and properties of SiO₂–NiCr composites can be tailored by controlling the component ratio and consolidation conditions.

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Conflict of interest

The authors declare that they have no competing interests.

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