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Simulating multi-material specimen manufacturing from VZh159 and CuCr1Zr alloys via SLM method: Computational modeling and experimental findings

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Abstract. Manufacturing of multi-material products through layer-by-layer synthesis poses various challenges encompassing process parameter optimization, equipment calibration, and the mitigation of warping and internal stresses within the manufactured parts. The article investigates the feasibility of simulating the selective laser melting (SLM) process for manufacturing multi-material components, exemplified through specimens composed of the VZh159 nickel alloy and CuCr1Zr copper alloy. The study entails numerical simulations of the printing process, which were then validated against real specimens produced through SLM. Each test specimen was vertically divided into three parts: the top and bottom sections consisted of the VZh159 alloy, while the central part was composed of the CuCr1Zr alloy. Simulations involved using identical process parameters as employed in the printing process. Thermal and mechanical analyses for each part of the multi-material specimen were sequentially addressed, transferring the outcomes of the preceding analysis as initial conditions for subsequent calculations. The study concludes that while the obtained simulation results are indicative, they do not precisely capture the deformation observed in the specimens manufactured via the SLM method. The numerical values of deformations derived from simulation results slightly underestimate the actual deformations, attributed to limitations in the chosen calculation algorithms. For future utilization of numerical computer simulation in the SLM manufacturing of multi-material specimens, the study suggests the necessity of implementing a seamless, continuous simulation process without transitions between different parts of the specimen. This entails considering the entire manufacturing process without segregating sections, ensuring a comprehensive account of continuous deformation and stress accumulation throughout fabrication.

Keywords: multi-material, thermal and mechanical analysis, simulation of the process, selective laser melting, VZh159, CuCr1Zr, deformation

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Изготовление мультиматериальных образцов из сплавов ВЖ159 и БрХЦрТ В методом СЛП: численное компьютерное моделирование и экспериментальные результаты

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Аннотация. Изготовление мультиматериальных изделий методом послойного синтеза кроет в себе множество вопросов, связанных как с технологическими параметрами и подготовкой оборудования, так и с короблениями и внутренними напряжениями получаемых деталей. В данной статье показана возможность моделирования процесса селективного лазерного плавления (СЛП) в части создания мультиматериальных деталей на примере образцов из никелевого сплава ВЖ159 и медного сплава БрХЦрТ В. Результаты численного моделирования процесса печати были верифицированы на основе изготовленных образцов. Исследуемый образец был разделен на 3 части по вертикали: нижняя и верхняя части изготавливались из сплава ВЖ159, центральная – из сплава БрХЦрТ В. Для проведения численного моделирования использовались такие же технологические параметры, как и для печати. Последовательно решались задачи термического и механического анализов для каждой из частей мультиматериалоного образца с передачей результатов расчета предшествующей задачи в начальные условия последующей задачи. В результате проведенного исследования установлено, что полученные результаты моделирования являются показательными, однако не совсем точно описывают деформацию образца, изготовленного методом СЛП. Численные значений деформаций, полученные по результатам моделирования, несколько меньше, чем реальные, что связано с несовершенством выбранных алгоритмов расчета. Для возможности дальнейшего использования численного компьютерного моделирования процесса выращивания мультиматериальных образцов методом СЛП необходимо реализовать непрерывный процесс моделирования, без перехода между частями образца, когда одна часть начинает рассматриваться системой как подложка. Необходим учет непрерывного изготовления образца и, соответственно, непрерывного деформирования и накопления напряжений.

Ключевые слова: мультиматериал, термический и механический анализ, моделирование процесса, селективное лазерное плавление, ВЖ159, БрХЦрТ В, деформация

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Introduction

Today, numerous high-tech engineering challenges necessitate the use of products crafted from metals and alloys possessing enhanced and distinct properties that cannot be attained through a singular material composition [1]. Multi-material approaches prove invaluable in addressing such issues – encompassing the incorporation of multiple materials or alloys into a product's composition. This method enables the amalgamation of their properties or facilitates precise distribution of these attributes, thereby achieving desired qualities like localized wear resistance, elevated thermal conductivity, thermal insulation, resistance to chemical corrosion, among others, at specific points within a product or component [2].

The classification of multi-materials includes compositions like polymer–metal, metal–metal (bimetal), metal–ceramic, among others [3]. Bimetallic products are combinations of two metals or alloys achieved by welding or soldering, effectively mitigating their respective drawbacks while preserving the desired properties of each [4]. For example, copper-based alloys such as GRCop-84 exhibit remarkably high thermal conductivity, facilitating rapid cooling, elevated temperature strength with minimal thermal expansion, and substantial resistance to oxidation. This makes them suitable for applications in combustion chambers, jet sleeves of regenerative-cooled rocket engines (jet linings), and areas exposed to high-temperature gas flows [5; 6]. Conversely, nickel-based alloys like Inconel 718 are renowned for their resistance to high-temperature corrosion, making them prevalent in aerospace applications, especially in gas-turbine and rocket engines due to their impressive tensile and tear strength, coupled with oxidation resistance at elevated temperatures. Nonetheless, these alloys have low thermal conductivity [7; 8]. Consequently, employing copper alloys atop nickel alloys (like Inconel 718 or similar) can enhance the thermal conductivity of products while upholding their strength characteristics [5].

To fabricate these products, both conventional technologies and additive manufacturing techniques are viable, enabling the production of items with intricate, sophisticated geometries [1; 3]. Presently, scientific literature exists detailing the characteristics of bimetallic and functional-gradient products falling under the "nickel alloy – copper alloy" classification (In718–Cu; In718–GRCop-84). These studies employ various methods, including direct energy and material supply processes [5; 6; 9], as well as synthesis processes on substrates, such as selective laser melting (SLM) [10; 11]. The SLM process involves numerous parameters that significantly impact the resultant properties, internal stresses, and potential defects in the manufactured materials and products [12–14]. Fine-tuning these process parameters is a crucial and indispensable aspect of the product development process [15]. Using numerical computer simulations proves pivotal in reducing the duration of parameter refinement and minimizing the cost of potential errors, particularly when fabricating products with intricate geometries [16–18].

Up to this point, simulations of the SLM process have been extensively documented [14; 16; 17; 19]. However, these studies have not addressed the simulation challenges associated with manufacturing products from multi-material compositions, particularly bimetallic products. Therefore, advancing the effective application of additive technologies in producing bimetallic products/parts for diverse purposes necessitates exploring the feasibility of simulating the SLM process for such products.

The objective of this study is to conduct numerical computer simulations of the SLM manufacturing process for multi-material specimens composed of the VZh159 nickel alloy and CuCr1Zr copper alloy. Subsequently, the obtained simulation results will be validated based on the specimens manufactured in the real-world setting.

Materials and methods

The numerical computer simulation of the multi-material specimen growth via the SLM method was conducted using the finite-element analysis package "ANSYS Workbench 2019 R2" with the utilization of the "Transient Thermal" and "Static Structural" modules [20]. Fig. 1 illustrates the model of the specimen, delineating the material composition of its three distinct parts: top, middle, and bottom. The simulation process involved a sequential resolution of the thermomechanical problem for each segment of the specimen. Initially, the thermal aspect was addressed using the "Transient Thermal" module, followed by the mechanical problem tackled through the "Static Structural" module. Fig. 2 provides a block diagram outlining the steps involved in the numerical computer simulation.

The simulation process for the product growth via the SLM method utilized specific parameters: for the VZh159 alloy – laser power of 275 W, scanning rate at 760 mm/s, distance between laser passes set at 0.1 mm, and a layer thickness of 0.05 mm; for the CuCr1Zr alloy – laser power of 400 W, scanning rate at 300 mm/s, distance between laser passes at 0.15 mm, and a layer thickness of 0.05 mm. Detailed physical and mechanical properties of the alloys employed in the simulation process are provided within a referenced Table.

Spherical powders of the VZh159 alloy (with distribution quantiles d_{10} = 17 μm, d_{50} = 32 μm, d_{90} = 55 μm) and CuCr1Zr alloy (with d_{10} = 14 μm, d_{50} = 29 μm, d_{90} = 52 μm) were used to create bimetallic material specimens. Fig. 3 displays SEM images depicting the particles of these powders.

The manufacturing process occurred within an inert gas atmosphere employing the SLM280HL machine (SLM Solutions GmbH, Germany). This machine is equipped with an ytterbium fiber laser possessing a wavelength of 1070 nm, a maximum power output of 400 W, a minimum laser beam diameter of 80 μm, and a maximum scanning rate of 15 m/s. The produced specimens were constructed with the upper and lower parts comprised of VZh159 alloy, while the middle sections were fashioned from CuCr1Zr alloy.

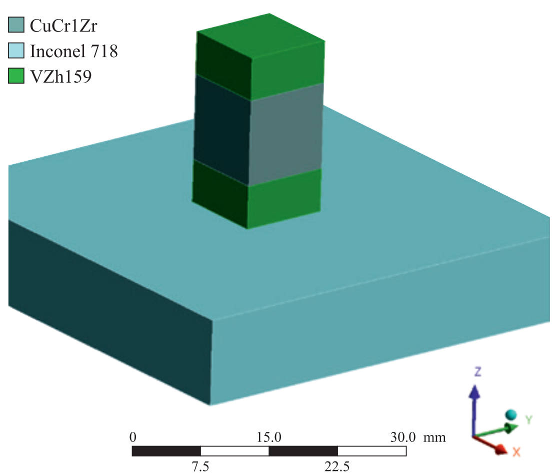


Fig. 1. Initial design of the multi-material specimen

Рис. 1. Исходная модель мультиматериального образца

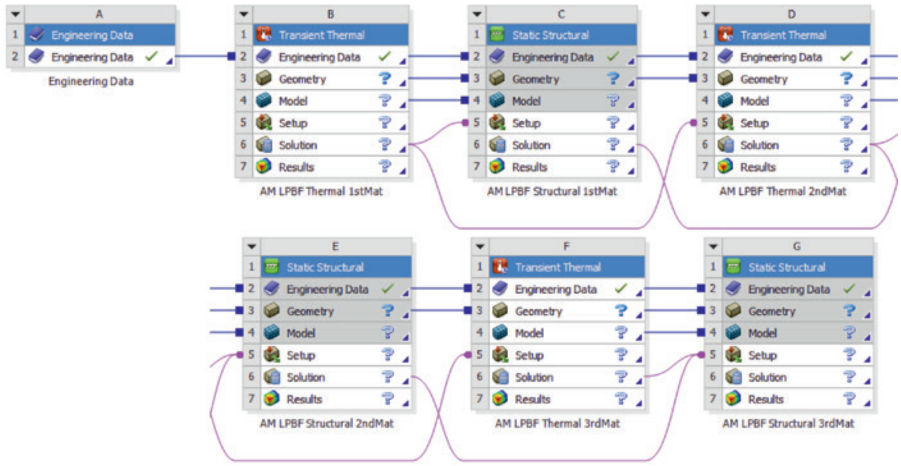


Fig. 2. Block diagram of computer simulation for manufacturing multi-material specimens

Рис. 2. Блок-схема численного компьютерного моделирования изготовления мультиматериальных образцов

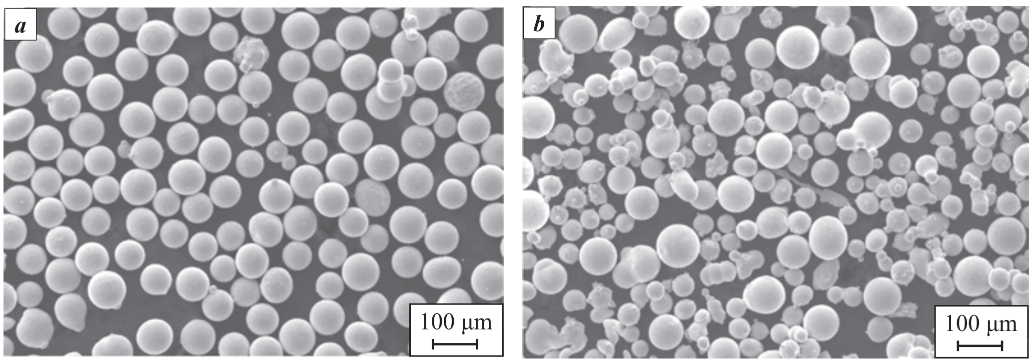


Fig. 3. SEM image of CuCr1Zr (***a***) and VZh159 (***b***) alloy powders used in the study

Рис. 3. СЭМ-изображения используемых в исследовании порошков сплавов БрХЦрТ В (***a***) и ВЖ159 (***b***)

Physical and mechanical properties of modeled alloys

Физико-механические свойства моделируемых сплавов

Alloy	Tempera-ture, °C	Density, kg·m^3	Thermal-expansion coefficient, 10^{-5} °C^{-1}	Thermal conductivity, W/(m·°C)	Specific heat capacity, J/(kg·°C)	Elasticity	
						Young's modulus, GPa	Poisson ratio
VZh159	25	8.43	11.47	11.01	0.39	213.18	0.31270
	100	8.41	11.82	12.19	0.41	208.37	0.31473
	500	8.27	13.85	18.38	0.47	180.35	0.32554
	1000	8.04	16.41	26.03	0.56	139.68	0.33905
	1100	7.99	16.92	27.55	0.71	130.79	0.34175
	1350	7.65	25.68	27.67	0.69	–	–
	2000	7.09	31.97	35.97	0.76	–	–
CuCr1Zr	25	8.93	16.34	92.97	0.01	129.53	0.34903
	100	89.00	16.59	101.86	0.01	125.96	0.35319
	500	8.71	18.15	134.91	0.01	101.42	0.37662
	1000	8.43	20.40	162.42	0.01	57.78	0.40650
	1100	8.10	35.51	160.79	5.17	–	–
	1350	7.76	38.22	167.71	0.50	–	–
	2000	7.18	41.26	180.12	0.50	–	–

The examination of the acquired specimens was conducted using a light optical microscope called “Leica DMI 5000” (Leica Microsystems, Germany). To facilitate the examination process, the specimens were sectioned using the electroerosion method.

Results and discussion

Fig. 4 illustrates the outcomes of simulating the SLM manufacturing process for multi-material specimens, showcasing the deformation fields along the *Y*-axis. Notably, inward deformation of the specimen’s sides is evident, reaching a maximum deformation of 83 μm.

Particularly, the middle section of the specimen made of CuCr1Zr experiences the most significant deformation. Additionally, the top part composed of VZh159 displays considerable deformation, especially at the interfaces between materials.

In Fig. 5, the simulation results portray the stress fields following the production of multi-material specimens via the SLM method. The highest stress values, approximately 900 MPa, are observed at the corners of the specimen at the material interfaces. Elevated stress, ranging from 400 to 500 MPa, is noticeable in the upper part of the specimen fabricated from VZh159. Comparatively, the lowest stress values do not exceed 100 MPa.

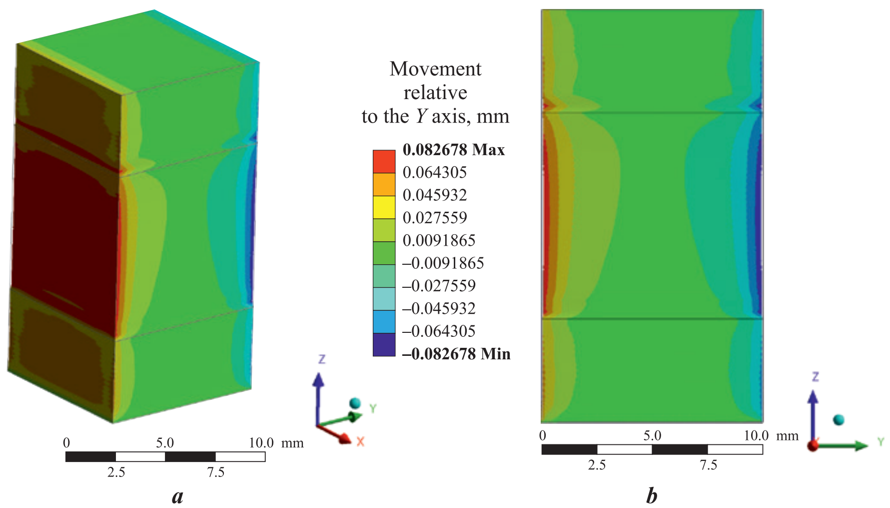


Fig. 4. Results of simulating of multi-material specimen manufacturing – specimen deformation along the *Y* axis
a – general view, ***b*** – view in the *X* plane

Рис. 4. Результаты моделирования процесса изготовления мультиматериального образца – его деформации по оси *Y*
a – общий вид, ***b*** – вид в плоскости *X*

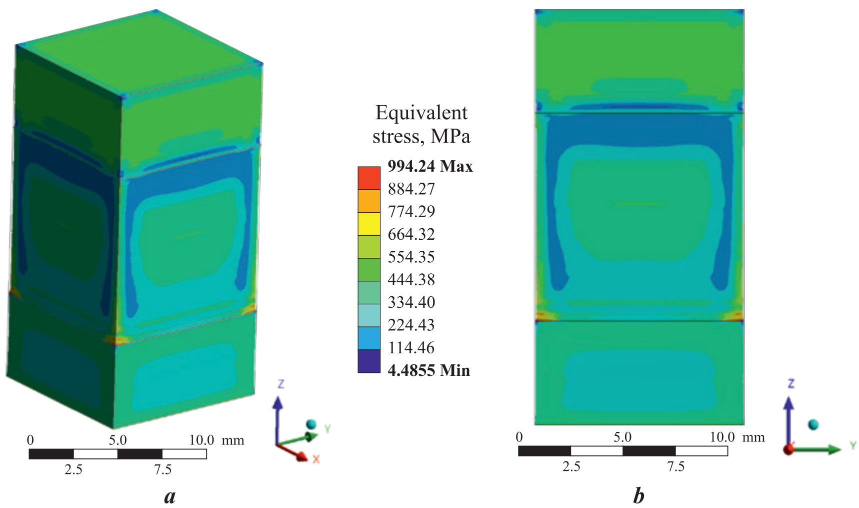


Fig. 5. Results of simulating of multi-material specimen manufacturing – specimen stress
a – general view, ***b*** – view in the *X* plane

Рис. 5. Результаты моделирования процесса изготовления мультиматериального образца – напряжения образца
a – общий вид, ***b*** – вид в плоскости *X*

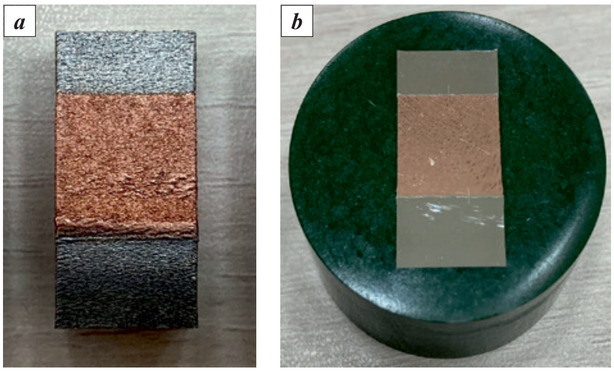


Fig. 6. Manufactured multi-material specimen (***a***) and thin section prepared from the specimen (***b***)

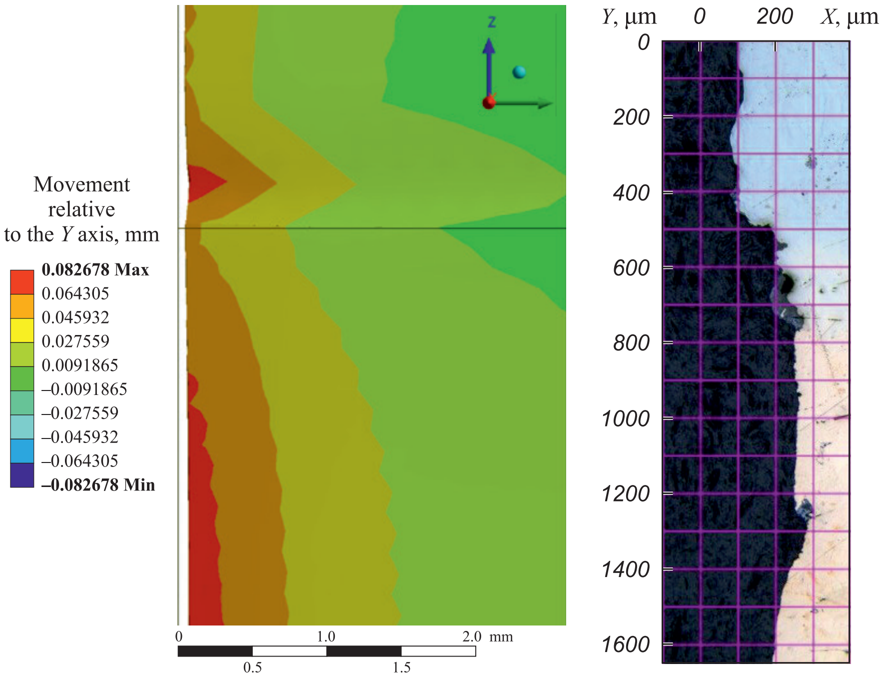
Рис. 6. Изготовленный мультиматериальный образец (***a***) и подготовленный шлиф образца (***b***)

Fig. 6 displays the multi-material specimens made using the SLM method. Visual examination indicates the absence of significant deformations or visible defects such as fractures or failures.

In Fig. 7, the verification of the deformation simulation for the specimen produced via the SLM method is presented, specifically at the interface between its top part (constructed from VZh159) and the middle part (constructed from CuCr1Zr).

The simulations depicted in Fig. 7, *a*, revealed deformations ranging from 64 to 83 μm at the interface between the top and middle sections of the specimen, illustrating distinct inward bending occurring separately in both the top and middle parts. Upon experimental examination of the SLM-manufactured specimen (Fig. 7, *b*), the deformation at the interface measured approximately 100 μm, slightly exceeding the simulated values (with the largest deviation being 36 μm). Inward bending with maximum deformation near the interface is predominantly observed in the middle part of the specimen constructed from CuCr1Zr.

The disparity between the simulation results and experimental data might be attributed to the inherent characteristics of the simulation process. As the simulation initiates the fabrication of the top part of the VZh159 specimen, its middle part ceases to influence stress and deformation calculations, being treated as part of the substrate. This leads to limitations in the acquired values of stresses and deformations. Consequently, the distinct nature of specimen deformation, observed when the simulated specimen deforms in two separate sections, is a direct consequence of this phenomenon. This limitation underscores the challenges in employing simulations for



a ***b***

Fig. 7. Validation of deformation simulation at the interface between the top and middle parts of the VZh159 and CuCr1Zr alloys in the multi-material specimen produced by SLM

a – simulation results, ***b*** – experimental specimen

Рис. 7. Верификация моделирования деформации мультиматериального образца, изготовленного методом СЛП, на границе раздела между верхней и средней частями из сплавов соответственно ВЖ159 и БрХЦрТ В

a – результаты моделирования, ***b*** – экспериментально изготовленный образец multi-material manufacturing processes using SLM method.

Nonetheless, the deformation values obtained through simulation generally present a representative approximation, closely aligning with the experimental values. However, for more intricate structures, optimizing the system becomes essential to achieve better alignment with real-world results.

Conclusion

Based on the completed research results, several conclusions have been drawn regarding the numerical computer simulation of the manufacturing process for multi-material specimens made from the VZh159 nickel alloy and CuCr1Zr copper alloy.

1. The simulation results, while indicative, do not precisely mirror the deformation observed in the specimen produced via the SLM method. The numerical values of deformations obtained from simulations (from 64 to 83 μm) slightly underestimate the actual deformations (approximately 100 μm). This discrepancy is attributed to the imperfections in the chosen calculation algorithms, particularly when the system stops considering the middle part of the specimen in the calculation and treats it solely as a substrate after initiating the calculation of the top part of the specimen manufacturing.

2. To enable the continued utilization of numerical computer simulation for the growth of multi-material specimens via the SLM method, it is imperative to implement a seamless simulation process without the discontinuity between different parts of the specimen. This involves accounting for the continuous manufacturing process of the specimen, thereby considering uninterrupted deformation and accumulation of stresses throughout the fabrication procedure.

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E. M. Farber – conducted critical literature analysis, contributed to manuscript writing, participated in result analysis and discussion.
E. B. Borisov – planned and executed experiments, handled specimen manufacturing, contributed to result analysis and discussion.
A. A. Popovich – developed key conceptual ideas, outlined the study’s objectives, contributed to result analysis and discussion.

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