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COOLING METHODS FOR LIQUID ROCKET ENGINE NOZZLES

This study presents a review and comparative analysis of design approaches, material selection, and manufacturing technologies for regeneratively cooled liquid rocket engine nozzles. The thermophysical and mechanical properties of AISI 316 stainless steel, Inconel alloy, and CuCrZr copper alloy were analyzed to assess their applicability for different nozzle components. In addition, the strength characteristics of welded joints between similar and dissimilar materials produced by TIG and MIG welding were experimentally evaluated. The results demonstrate that Inconel exhibits the highest suitability for the load-bearing section of the nozzle due to its superior high-temperature strength and structural stability, whereas CuCrZr provides the most effective solution for the inner cooled wall because of its high thermal conductivity and heat removal capability. The study also shows that the use of hybrid material configurations combined with optimization of welding and joining technologies contributes to improved cooling efficiency, enhanced mechanical integrity, and increased operational reliability of liquid rocket engine nozzles. The obtained results may serve as a basis for the development and manufacturing of advanced regeneratively cooled propulsion systems.

Keywords: liquid rocket engine, metallic materials, cooling system, CuCrZr, Inconel, AISI 316

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Сұйық зымыран қозғалтқышы соплоларын салқындату әдістері

Бұл зерттеуде регенеративті салқындатылатын сұйық зымыран қозғалтқышы соплоларының конструкциялық шешімдері, материалдарды таңдау және дайындау технологиялары бойынша шолу және салыстырмалы талдау ұсынылған. Соплоның әртүрлі бөліктерінде қолдану мүмкіндігін бағалау мақсатында AISI 316 тот баспайтын болатының, Inconel қорытпасының және CuCrZr мыс қорытпасының жылуфизикалық және механикалық қасиеттері талданды. Сонымен қатар, TIG және MIG дәнекерлеу әдістерімен алынған біртекті және әртекті материалдардың дәнекерленген қосылыстарының беріктік сипаттамалары тәжірибелік түрде бағаланды. Нәтижелер көрсеткендей, жоғары температурадағы беріктігі мен құрылымдық тұрақтылығының арқасында Inconel соплоның күштік бөлігі үшін ең қолайлы материал болып табылады, ал жоғары жылуөткізгіштігі мен жылуды әкету қабілетінің арқасында CuCrZr салқындатылатын ішкі қабырға үшін ең тиімді шешім болып саналады. Сондай-ақ зерттеу нәтижелері гибридті материалдық конфигурацияларды қолдану және дәнекерлеу мен біріктіру технологияларын оңтайландыру салқындату тиімділігін арттыруға, механикалық тұтастықты жақсартуға және сұйық зымыран қозғалтқышы соплоларының пайдалану сенімділігін жоғарылатуға мүмкіндік беретінін көрсетті. Алынған нәтижелер болашақта регенеративті салқындатылатын жетілдірілген қозғалтқыш жүйелерін әзірлеу мен өндіру үшін негіз бола алады.

Түйін сөздер: сұйық зымыран қозғалтқышы, металл материалдар, салқындату жүйесі, CuCrZr, Inconel, AISI 316.

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Методы охлаждения сопел жидкостных ракетных двигателей

В данной работе представлен обзор и сравнительный анализ конструктивных подходов, выбора материалов и технологий изготовления сопел жидкостных ракетных двигателей с регенеративным охлаждением. Проведён анализ теплофизических и механических свойств нержавеющей стали AISI 316, никелевого сплава Inconel и медного сплава CuCrZr для оценки возможности их применения в различных элементах сопла. Кроме того, экспериментально исследованы прочностные характеристики сварных соединений однородных и разнородных материалов, полученных методами сварки TIG и MIG. Полученные результаты показали, что сплав Inconel является наиболее подходящим материалом для силовой части сопла благодаря высокой жаропрочности и структурной стабильности, тогда как сплав CuCrZr обеспечивает наиболее эффективное решение для внутренней охлаждаемой стенки за счёт высокой теплопроводности и способности к отводу тепла. Также установлено, что применение гибридных конфигураций материалов в сочетании с оптимизацией технологий сварки и соединения способствует повышению эффективности охлаждения, улучшению механической целостности и увеличению эксплуатационной надёжности сопел жидкостных ракетных двигателей. Полученные результаты могут служить основой для разработки и производства перспективных двигательных систем с регенеративным охлаждением.

Ключевые слова: жидкостный ракетный двигатель, металлические материалы, система охлаждения, CuCrZr, Inconel, AISI 316.

Introduction

A liquid rocket engine (LRE) is a rocket engine that operates on liquid propellants and is capable of functioning both in the atmosphere and in outer space. LREs are the primary type of propulsion system used in spacecraft and are widely applied in ballistic, anti-aircraft, and research rockets. Depending on their purpose, propulsion, booster, attitude control, braking, steering, and micro rocket engines are distinguished. Most modern LREs operate on bipropellant systems and consist of a combustion chamber, nozzle, turbopump unit, gas generator, control system, and other auxiliary components. Fuel and oxidizer are supplied through injectors into the combustion chamber, where, after mixing and ignition, high-temperature combustion products with temperatures reaching 3700-3900 K are generated and subsequently discharged through the nozzle to produce thrust [1].

One of the key challenges in LRE design is ensuring the thermal resistance of the combustion chamber and nozzle. For this purpose, both active and passive cooling methods are employed. The most widely used active cooling method is regenerative cooling, in which the propellant circulates through channels within the chamber and nozzle walls, simultaneously cooling the structure and being preheated before entering the combustion chamber. In contrast to active cooling, passive cooling does not involve preliminary heat removal; therefore, thermal protection materials and coatings are incorporated into the structure [2].

According to the operating cycle, LREs are classified into open-cycle and closed-cycle engines. In open-cycle engines, the gas generator exhaust products are discharged into the environment after passing through the turbines, whereas in closed-cycle engines these products are directed into the combustion chamber for afterburning. The use of a closed cycle enables an increase in combustion chamber pressure and provides a higher specific impulse [3].

Active cooling represents a more complex and costly system compared with passive cooling; however, its application is essential for the operation of high-performance LREs functioning under extremely high temperatures, particularly engines operating on liquid oxygen and hydrogen [4].

The choice of cooling method is determined by the design features of the engine, the type of propellant used, the level of thermal loads, as well as the requirements for engine efficiency and service life. In modern LREs, regenerative cooling has become the most widely adopted approach, especially in closed-cycle engines, since this method ensures efficient heat removal through propellant circulation within cooling channels and contributes to improving the overall energy efficiency of the engine.

Nozzle Cooling Methods

From a technological perspective, the design of a liquid rocket engine (Figure 1) can conventionally be divided into two main parts: the combustion chamber and the nozzle section. The initial data for designing the combustion chamber and nozzle primarily include the geometric parameters of the structure, including the shape, volume, configuration, and angles of the channels through which the coolant circulates. Based on these parameters, calculations of heat fluxes between the channel walls and the coolant are performed, the coolant flow velocity is determined, and the thermophysical properties of materials and fuel components, as well as their ability to absorb and transfer thermal energy, are analysed. Depending on the structural configuration and the selected cooling method, the main materials for the combustion chamber and nozzle are determined [5].

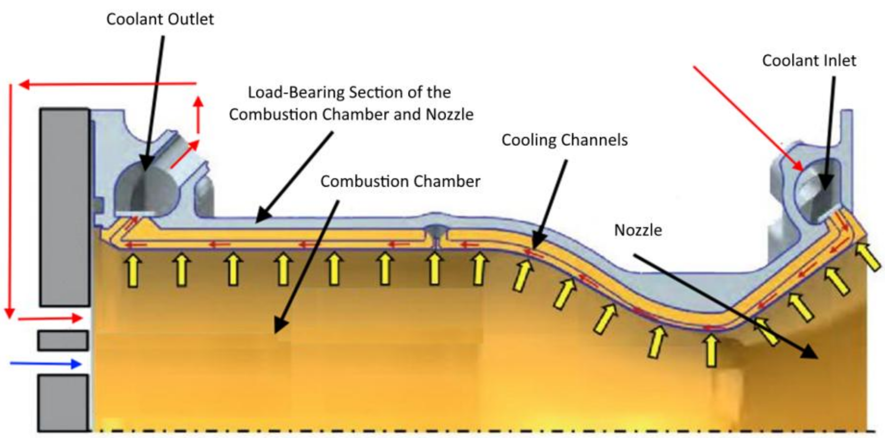


Figure 1 - Combustion Chamber with Liquid Rocket Engine Nozzle

At present, various regenerative cooling systems are employed in LRE nozzle designs, among which channel-wall, tubular, and sandwich-wall structures are the most widely used.

Previously, both channel-wall and sandwich-wall designs were widely used in rocket engines for cooling combustion chambers. As a rule, the inner liner was manufactured from a copper-chromium alloy in which grooves or channels were machined to intensify heat transfer. The liner was then joined to an outer shell or cover sheet made of low-alloy steel, stainless steel, or nickel alloy. The inner liner was typically connected to the outer shell by brazing. Channel-wall designs were mainly applied in combustion chambers; however, in high-performance engines this cooling method was also used in nozzles [6].

A similar design was implemented in the RD-107 engine, in which the nozzle was produced as a sandwich structure: the inner lining was manufactured from a copper-chromium alloy (Cu-Cr), while corrugated sheet metal was used as the separator. The outer shell was generally made of alloyed or stainless steel, as well as nickel alloys. All structural elements were joined by brazing, while the corrugated inserts formed channels for coolant circulation. Such a design provides an effective combination of high strength and intensive heat dissipation. Channel-wall and sandwich-wall structures are considered more manufacturable and cost-effective in production compared with tubular nozzles. However, their main disadvantage is their relatively high mass, which is particularly critical for high-performance rocket engines. It should be noted that the inner lining and outer shell were initially connected mainly by bolted joints, which led to leakage between the cooling channels. After the Second World War, a pressure brazing method was developed, providing a reliable connection between the machined liner and the outer shell. This technological solution became an important milestone in the development of regeneratively cooled nozzle designs and made it possible to improve the efficiency, tightness, and reliability of liquid rocket engines [7].

The nozzle of the Space Shuttle main engine was a brazed tubular structure consisting of 1080 A286 stainless steel tubes joined together and connected to an outer shell made of Inconel 718 alloy. The brazing process represented a complex technological challenge, since it was necessary to account for the difference in coefficients of thermal expansion between A286 and Inconel 718. This required high precision in selecting brazing conditions to prevent the development of residual stresses, deformation, and loss of structural tightness under thermal loading [8].

In Europe, the nozzles of the Vulcain engine were manufactured by Volvo using an original tubular technology. The design included Inconel 600 alloy tubes with a square cross-section wound in a spiral configuration, which eliminated the need for additional tapering. Unlike conventional brazing, the tubes were joined using gas tungsten arc welding (GTAW) with the formation of fillet welds. For the upgraded version of the Vulcain engine, a new sandwich-wall expansion nozzle design was developed. In this configuration, the inner liner was produced in the form of a machined channel covered by a closing sheet. The sheet was joined to the liner by full-penetration laser welding, providing high joint strength and tightness (Figure 2). According to published data, the structure was manufactured from stainless steel [9].

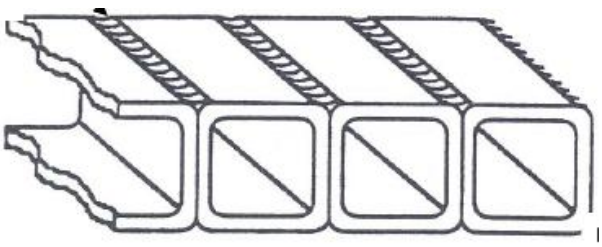


Figure 2 - Schematic Diagram of the Volvo Welded Square-Tube Structure

A combined manufacturing technology was applied in the production of the combustion chamber and nozzle assembly of the LCUSP rocket engine. The inner wall (liner) was manufactured from a copper alloy with high thermal conductivity, providing intensive heat dissipation and efficient cooling of the structure. The outer load-bearing jacket was made of a heat-resistant nickel alloy characterized by high strength and resistance to high-temperature loads. The LCUSP engine nozzle had a tubular design [10].

To produce the load-bearing nozzle jacket from a heat-resistant alloy on a copper liner, NASA specialists developed and patented an innovative laser deposition method using wire feed, known as Laser Wire Direct Closeout (LWDC). This technology provides high-precision layer-by-layer metal deposition and enables the formation of a strong bond between the copper liner and the outer heat-resistant alloy [11].

To implement LWDC technology in the production of rocket engine components, including nozzle assemblies, mathematical models of the heating, melting, and solidification processes of materials with different coefficients of thermal expansion were developed. The use of these models made it possible to predict the thermal behavior of materials during deposition, minimize residual stresses, and ensure the production of a bimetallic structure with the required mechanical and thermophysical characteristics [12].

Reference [13] also considers the V-2 rocket engine equipped with a short expansion nozzle of double-wall construction integrated into the combustion chamber. The nozzle was manufactured from low-alloy steel of the 6000 series. Cooling of the chamber and nozzle was achieved by circulating a fuel mixture consisting of 75% alcohol and 25% water, while film cooling was additionally applied in the most highly loaded zones. Liquid oxygen was supplied through aluminium tubes from the turbopump unit to 18 burner cups, which significantly complicated the engine design and assembly.

The authors of [14] described the NAA A6/A7 (Redstone) engine, which employed a double-wall sheet-metal structure welded into an integral shell with a relatively short expansion nozzle.

Reference [15] examines the Reaction Motors XLR-10 rocket engine used in the US Navy Viking research rocket. In this design, the double-wall nozzle elements were manufactured by welding; however, instead of steel, Nickel 200 sheet nickel was used, which improved corrosion resistance and enhanced mechanical performance at elevated temperatures.

According to [16], the combustion chambers and nozzles of the rocket engines used in the Apollo programme had a tubular design, in which the combustion chamber tubes gradually expanded to form the nozzle section of the engine.

Reference [17] notes that the nozzle of the European Aestus upper-stage engine was manufactured from Haynes 25 sheet alloy, characterized by high heat resistance and strength at extreme temperatures. The study also considers the nozzle of the Apollo Service Propulsion System engine, designed as a welded structure made of C103 niobium alloy and titanium, which provided high performance under significant thermal and mechanical loads.

Reference [18] provides a description of the F-1 engine, in which the nozzle was manufactured from Hastelloy-C sheet alloy in the form of a welded double-wall structure. Nozzle cooling was achieved by circulating hot gas exiting the turbine through the cooling passage, which enabled effective reduction of thermal loading on the structure.

The conducted analysis of existing regenerative cooling nozzle designs for liquid rocket engines makes it possible to establish a general understanding of current technological solutions and prospects for their further development. The reviewed designs and manufacturing methods are of practical interest for future studies aimed at developing an optimal nozzle configuration that ensures efficient cooling and high operational reliability of the liquid rocket engine.

At present, a programme-targeted research project aimed at the development of a liquid rocket engine is being implemented by scientific specialists in Kazakhstan. The engine under development operates on bipropellant fuel, using liquid oxygen as the oxidizer and ethanol as the fuel. During combustion of this fuel mixture, the temperature of combustion products reaches 3000-3500 K at a combustion chamber pressure of up to 10 MPa.

Operation of LREs under conditions of high temperatures and pressures results in significant thermal and mechanical loads on the combustion chamber and nozzle assembly. Therefore, ensuring stable and reliable engine operation requires not only the use of high-strength and heat-resistant materials but also the development of an efficient regenerative cooling system. Particular importance is attached to the selection of nozzle design, manufacturing technology, and the combination of materials with high thermophysical and mechanical properties. The authors have experience working with a wide range of materials in the fields of materials science and rocket engineering [19-33].

The aim of this study is to analyze materials, design solutions, and manufacturing technologies for regeneratively cooled nozzles intended for a liquid rocket engine operating on liquid oxygen and ethanol.

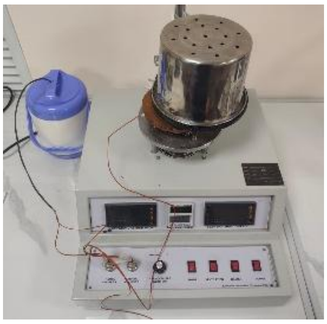
Materials and Methods

For this study, three metallic alloys most commonly used in the design of regeneratively cooled LRE nozzles were selected: AISI 316 stainless steel, Inconel nickel alloy, and CuCrZr copper-chromium-zirconium alloy. The selection of these materials was determined by their widespread application in high-temperature components of liquid rocket engines due to the combination of their mechanical and thermophysical properties.

The study included the determination of tensile strength and thermal conductivity of the materials within the temperature range from 25 to 800 °C, taking into account the permissible temperature limits for each alloy. Tensile tests were performed using an RMG-100 tensile testing machine (Figure 3a) in accordance with the requirements of GOST 1497-84. Prior to testing, the specimens were maintained at the specified temperature for a predetermined period to ensure uniform heating of the material.

The thermal conductivity coefficient was determined using a DRP-II analyzer (Figure 3b) in accordance with ASTM C177-19 and GOST 7076-99 procedures. Heating of the specimens to the required temperature was carried out in an SNOL muffle furnace (Figure 3c).


a) RMG-100 Tensile Testing Machine


b) DRP-II Thermal Conductivity Analyser


c) SNOL Muffle Furnace

Figure 3 - Experimental Facilities and Measuring Instruments

The reliability of regeneratively cooled nozzles during liquid rocket engine operation is largely determined by the strength and quality of welded joints, which ensure the integrated performance of different structural materials. As shown in Figure 4, one of the main technological challenges in manufacturing channel-type regeneratively cooled nozzles is joining the highly thermally conductive CuCrZr copper-chromium-zirconium alloy with low-thermal-conductivity materials, namely AISI 316 stainless steel and Inconel nickel alloy.

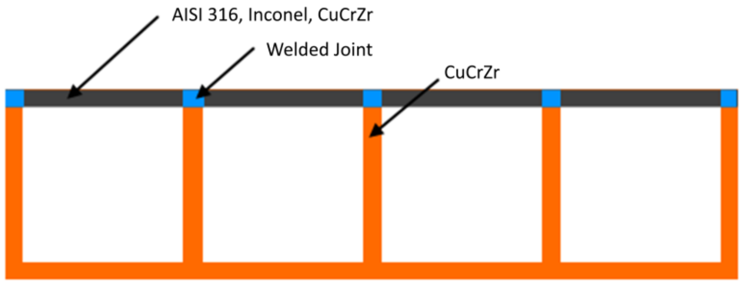


Figure 4 - Design of a Regeneratively Cooled Nozzle with Cooling Channels

To evaluate the strength of welded joints, plates made of AISI 316 steel, Inconel nickel alloy, and CuCrZr copper-chromium-zirconium alloy were prepared. The prepared specimens were welded together for subsequent investigation of joint strength for the following material combinations: CuCrZr-CuCrZr, CuCrZr-AISI 316, and CuCrZr-Inconel.

Welding was performed using argon arc equipment applying TIG and MIG technologies. A filler wire corresponding to the base material of the joined specimens was used as the filler material. After welding, the specimens underwent mechanical finishing, including surface cleaning, grinding, and polishing. The welding schemes of the investigated material pairs are presented in Figure 5.

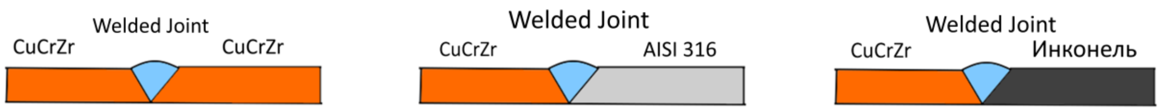


Figure 5 - Schematic Diagram of Welding Configurations for Material Pairs

Results and discussion

To ensure reliable operation of an LRE nozzle under conditions of high temperatures and pressure, the structure must combine the high strength and heat resistance of the outer load-bearing shell with the high thermal conductivity of the inner wall directly exposed to the heat flux. Therefore, within the framework of this study, an experimental investigation of the mechanical and thermophysical characteristics of the materials considered most promising for application in regeneratively cooled nozzles was carried out.

The objects of the study were AISI 316 stainless steel, Inconel nickel alloy, and CuCrZr copper-chromium-zirconium alloy. The conducted tests made it possible to evaluate changes in tensile strength and thermal conductivity of the materials as a function of temperature, as well as to determine the feasibility of their application in different components of the nozzle assembly. The results of the investigation of mechanical strength and high-temperature performance are presented in Table 1. For clarity, the obtained data are additionally presented in the form of diagrams in Figures 6 and 7.

Analysis of the results showed that the Inconel nickel alloy possesses the highest mechanical strength among the investigated materials. At room temperature, the ultimate tensile strength reaches approximately 1250 MPa and remains at about 700 MPa at 800 °C. In addition, Inconel exhibits a gradual increase in thermal conductivity with increasing temperature.

AISI 316 stainless steel demonstrates moderate strength characteristics of approximately 580 MPa at room temperature. However, at temperatures above 600 °C, a significant reduction in material strength is observed. Despite the increase in thermal conductivity with rising temperature, the thermophysical properties of AISI 316 remain relatively low compared with copper alloys, which limits heat dissipation efficiency in regenerative cooling systems.

Table 1 - Results of the Investigation of Material Strength and High-Temperature Performance for a Regeneratively Cooled Nozzle

Materials	Temperature, °C	Tensile Strength, MPa	Thermal Conductivity, W/(m·K)
AISI 316	25	580	14
	200	550	16
	400	450	19
	600	300	23
	800	140	27
Inconel	25	1250	11
	200	1220	13
	400	1140	17
	600	980	20
	800	700	24
CuCrZr	25	450	320
	200	400	300
	400	270	260
	600	140	220
	800	20	180

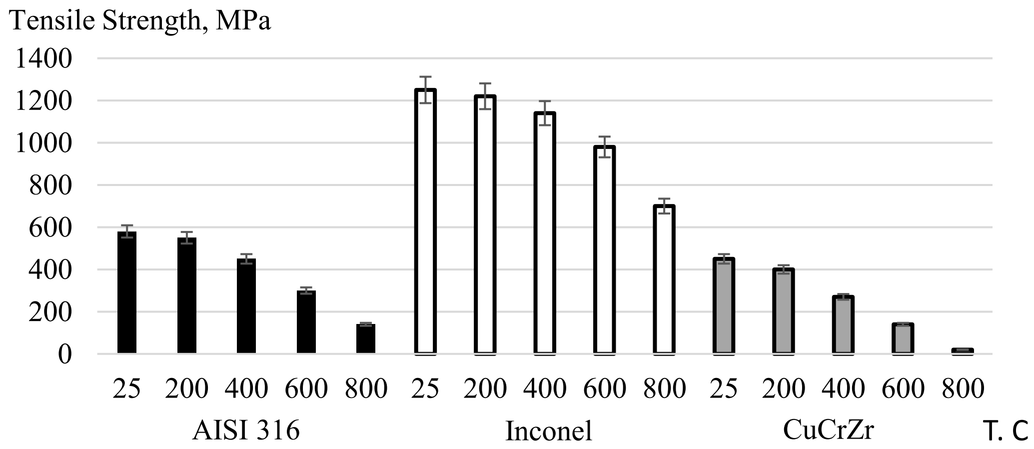


Figure 6 - Strength of Materials as a Function of Temperature

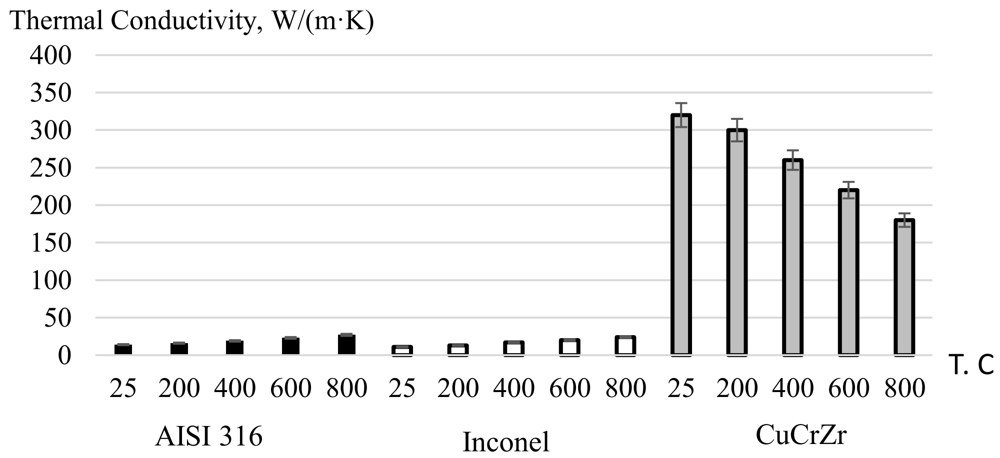


Figure 7 - Strength Characteristics of Materials for a Heat-Resistant Nozzle Assembly

Compared with AISI 316 steel, the Inconel nickel alloy is a more preferable material for manufacturing the outer load-bearing section of the nozzle due to its superior heat resistance and ability to retain mechanical properties at elevated temperatures. However, the application of Inconel is limited by its high cost and comparatively low availability. At the same time, AISI 316 steel is a more widely available and economically accessible material, making it suitable for use during the initial stages of development, manufacturing, and experimental validation of nozzle structures.The CuCrZr copper-chromium-zirconium alloy is characterised by significantly higher thermal conductivity compared with the other investigated materials. At room temperature, the thermal conductivity coefficient is approximately 320 W/(m·K), which ensures efficient heat dissipation under intensive thermal loads and makes this alloy a promising material for the inner wall of regeneratively cooled nozzles.

At the same time, the mechanical properties of the CuCrZr alloy are relatively low and amount to approximately 450 MPa at room temperature. With increasing temperature, both the strength and thermal conductivity of the material decrease: at 600 °C, the ultimate tensile strength is reduced to approximately 140 MPa, while the thermal conductivity coefficient decreases to 200 W/m·K. The obtained results indicate that, in order to ensure stable operation of the inner nozzle section manufactured from CuCrZr alloy, an efficient regenerative cooling system is required to prevent the material temperature from exceeding 600 °C. Maintaining the operating temperature within the range of approximately 25-200 °C is considered the most preferable, as high thermophysical and mechanical properties of the alloy are preserved within this range.

The conducted investigation of the mechanical and thermophysical properties of materials used in liquid rocket engine nozzle assemblies demonstrated that material selection should be carried out with consideration of the specific temperature and operating conditions of different structural components. The Inconel nickel alloy is the most preferable material for manufacturing the outer load-bearing nozzle elements due to its high heat resistance and ability to retain mechanical properties at elevated temperatures. The CuCrZr copper-chromium-zirconium alloy, characterised by high thermal conductivity, is most effective for application in the inner cooled section of the nozzle, where intensive heat removal is required. AISI 316 stainless steel may be used in regions with moderate thermal loading, as well as during experimental development and testing stages owing to its availability and relatively low cost.

Subsequently, the specimens were tested to evaluate the strength of welded joints. The results of the mechanical tests are presented in Table 2. Analysis of the obtained data shows that the highest values of weld strength were observed for CuCrZr-CuCrZr and CuCrZr-Inconel joints when using the TIG welding mode.

Table 2 - Tensile Strength of Welded Plates.

Welded Material Pairs	Tensile Strength of Welded Joint, MPa	
	TIG Mode	MIG Mode
CuCrZr-CuCrZr	210	90
CuCrZr-AISI 316	80	-
CuCrZr-Inconel	190	-

When welding the material pairs CuCrZr-CuCrZr, CuCrZr-AISI 316, and CuCrZr-Inconel, the tensile strength of the welded joints reached 210 MPa, 80 MPa, and 190 MPa, respectively. These values are significantly lower than the strength of the original CuCrZr material (450 MPa) and are approximately 2.14, 5.6, and 2.36 times lower, respectively. Thus, the strongest joint was obtained for the CuCrZr-CuCrZr pair, whereas the lowest strength was observed for the CuCrZr-AISI 316 combination.

When using the MIG welding mode, satisfactory joint quality was achieved only for the CuCrZr-CuCrZr pair, with a tensile strength of approximately 90 MPa, which is about five times lower than that of the base CuCrZr material (450 MPa). This indicates the lower effectiveness of the MIG process for the investigated dissimilar materials.

The obtained results demonstrate that, in some cases, the strength of welded joints is sufficient for the manufacture of regeneratively cooled nozzle structures and for testing as part of small liquid-propellant rocket engines. However, for application in large-scale liquid rocket engines operating at high pressures, thrust levels, and thermal loads, further improvement in welded joint strength is required. This may be achieved through optimisation of TIG welding parameters, development of post-weld heat treatment procedures, and the application of alternative joining technologies such as brazing, vacuum brazing, electron beam welding, and diffusion welding. It should be noted that conventional welding methods may in some cases be insufficiently effective due to significant differences in coefficients of thermal expansion, melting temperatures of materials, and limited mutual wettability of certain alloys.

Conclusion

This study presents an analysis of the designs and manufacturing technologies of regeneratively cooled liquid rocket engine nozzles, as well as an investigation of the mechanical and thermophysical properties of AISI 316, Inconel, and CuCrZr materials.

It was established that Inconel is the most suitable material for the load-bearing elements of the nozzle due to its high heat resistance, while CuCrZr is preferable for the inner cooled section owing to its high thermal conductivity. AISI 316 may be applied in less heavily loaded and experimental structures. It was demonstrated that heat transfer efficiency and material strength strongly depend on temperature, which requires a differentiated approach to material selection.

The investigation of welded joints revealed that the strongest welds are obtained using TIG welding, particularly for CuCrZr-CuCrZr and CuCrZr-Inconel pairs, whereas MIG welding demonstrates lower performance and limited applicability for dissimilar materials.

The presented results additionally indicate that the joining technology becomes one of the limiting factors in implementing multi-material nozzle structures. The relatively high strength obtained for CuCrZr-Inconel joints using TIG welding suggests the practical feasibility of hybrid nozzle manufacturing; however, the achieved strength levels indicate that the interface region remains a critical location requiring further optimisation. Future work should therefore focus on microstructural investigation of the weld zone, residual stress analysis, and evaluation of thermal cycling resistance under representative rocket engine conditions.

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