TOMSK POLYTECHNIC UNIVERSITY
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Министерство науки и высшего образования Российской Федерации
федеральное государственное автономное
образовательное учреждение высшего образования
«Национальный исследовательский Томский политехнический университет» (ТПУ)

Инженерная школа ядерных технологий

Направление подготовки 14.04.02 Ядерные физика и технологии

Отделение ядерно-топливного цикла

МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

Тема работы
Оценка механических свойств и адгезии SiC-покрытия на подложках из Zr-1Nb, приготовленных методом селективного лазерного спекания

УДК 621.039.53/.54:669.296:621.762.5

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Томск – 2021г.

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«Национальный исследовательский Томский политехнический университет» (ТПУ)

School: Engineering School of Nuclear Science and Technology

Field of training (Specialty): 14.04.02. Nuclear Power Engineering

Division: Nuclear Fuel Cycle

MASTER'S THESIS

Topic of research work
Mechanical and Adhesion Evaluation of SiC Coating on Zr-1Nb Substrates Prepared with Selective Laser Sintering Technique

UDC 621.039.53/.54:669.296:621.762.5

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Position	**Full name**	**Academic degree, academic rank**	**Signature**	**Date**
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Section "Financial Management, Resource Efficiency and Resource Saving"

Position	**Full name**	**Academic degree, academic rank**	**Signature**	**Date**
Associate professor	E.V. Menshikova	PhD		

Section "Social Responsibility"

Position	**Full name**	**Academic degree, academic rank**	**Signature**	**Date**
Associate professor	D. A. Verigin	PhD		

ADMITTED TO DEFENSE:

Director of the programme	**Full name**	**Academic degree, academic rank**	**Signature**	**Date**
Nuclear Power Installation Operation	V.V. Verkhoturova	PhD		

Tomsk – 2021

LEARNING OUTCOMES

Competence code	**Competence name**
Universal competences	
UC(U)-1	Ability to make critical analysis of problem-based situations using the systems analysis approach and generate decisions and action plans.
UC(U)-2	Ability to run a project at all life-cycle stages.
UC(U)-3	Ability to organize and lead the teamwork and generate a team strategy to achieve the target goal.
UC(U)-4	Ability to use modern communication technologies to realize academic and professional interaction.
UC(U)-5	Ability to analyze and account for cultural diversity in the process of intercultural interaction.
UC(U)-6	Ability to set and pursue individual and professional activity priorities and ways to modify professional activity based on the self-esteem.
General professional competences	
GPC(U)-1	Ability to formulate goals and objectives of the research study, select assessment criteria, identify priorities for solving problems.
GPC(U)-2	Ability to apply modern research methods, evaluate and present the results of the performed research.
GPC(U)-3	Ability to present research outcomes in the form of articles, reports, scientific reports and presentations using computer layout systems and office software packages.
Professional competences	
PC(U)-1	Ability to manage personnel, taking into account the motives of behavior and ways of developing business behavior of personnel, apply methods for assessing the quality and performance of personnel, develop and implement measures aimed at preventing industrial injuries and environmental violations.
PC(U)-2	Ability to develop and ensure the implementation of measures aimed at improving, modernizing, unifying manufactured devices, facilities and their components, developing standards and certificates, improving reliability of equipment operation.
PC(U)-3	Ability to apply basic methods, techniques and means of obtaining, storing, processing information to plan and manage the life cycle of manufactured products and their quality.
PC(U)-4	Ability to create theoretical and mathematical models describing the condensed state of matter, the propagation and interaction of radiation with matter, the physics of kinetic phenomena, processes in reactors, accelerators, the effect of ionizing radiation on materials, humans and environmental objects.
PC(U)-5	Ability to use fundamental laws in the field of nuclear physics, nuclear reactors, condensed matter, ecology in a volume sufficient for independent combination and synthesis of real ideas, creative self-expression.
PC(U)-6	Ability to evaluate prospects for the development of the nuclear industry, use its modern achievements and advanced technologies in research activities related to the development of technologies for obtaining new types of fuel and materials, radioactive waste management methods and techniques.

PC(U)-7	Ability to assess risks and determine safety measures applied for new facilities and technologies, draw up and analyze scenarios of potential accidents, develop methods to reduce the risk of their occurrence.
PC(U)-8	Ability to analyze technical and computational-theoretical developments, take into account their compliance with the requirements of laws in the field of industry, ecology and safety, and other regulations.
PC(U)-9	Ability to carry out independent experimental or theoretical research to solve scientific and technical problems using modern equipment, calculation and research methods.
PC(U)-10	Ability to draw up technical assignments, use information technology, standard design automation tools and application software packages in the design and calculation of nuclear facilities, materials and devices, apply knowledge of methods of ecological efficiency and economic-value analysis in the design and implementation of projects.
PC(U)-11	Ability to develop design process documentation, execute engineering design and production projects.
PC(U)-12	Ability to conduct training sessions and develop instructional materials for the training courses within the cycle of professional training programs (bachelor degree programs).

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School of Nuclear Science & Engineering

Field of training (specialty): 14.04.02 Nuclear Science and Technology

Specialization: Nuclear Power Engineering

Nuclear Fuel Cycle Division

APPROVED BY:
Program Director
_____________ Verkhoturova V.V.
«____» ____________ 2021

ASSIGNMENT
for the Graduation Thesis completion

In the form:

Master Thesis

For a student:

Group	**Full name**
0АМ9И	Ismail Omer Abubaker Amer

Topic of research work:

Mechanical and Adhesion Evaluation of SiC Coating on Zr-1Nb Substrates Prepared with Selective Laser Sintering Technique	
Approved by the order of the Director of School of Nuclear Science & Engineering (date, number):	№ 29-49/c dated January 29, 2021

Deadline for completion of Master Thesis:	05.06.2021

TERMS OF REFERENCE:

Initial date for research work: (the name of the object of research or design; performance or load; mode of operation (continuous, periodic, cyclic, etc.); type of raw material or material of the product; requirements for the product, product or process; special requirements to the features of the operation of the object or product in terms of operational safety, environmental impact, energy costs; economic analysis, etc.)	Mechanical and Adhesion Evaluation of SiC Coating on Zr-1Nb Substrates Prepared with Selective Laser Sintering Technique; powder of SiC was sintered on Zr-1Nb samples substrate with technique of SLS. Two samples were coated with 200 µm in different atmospheres (Air and Ar), by using mechanical investigations such as, micro indentation, scratch adhesion, and tribological tests, the surface profile of coating uniformity were investigated, the results achieved, products have not effect on the personnell, structures, and environment. the cost is lower than cost of accident.
List of the issues to be investigated, designed and developed (analytical review of literary sources with the purpose to study global scientific and technological achievements in the target field, formulation of the research purpose, design, construction, determination of the procedure for research, design, and construction, discussion of the research work results, formulation of additional sections to be developed; conclusions).	To review the literature To achieve the objective of study To conduct an experimental researches of coating surface profile, as well as coating integrity. To analysis the obtained results To make discussion and conclusion
List of graphic material (with an exact indication of mandatory drawings)	

Advisors to the sections of the Master Thesis (with indication of sections)	
Section	**Advisor**
One: Literature Review	Professor Lider Andrey Markovich.
Two: Materials and Methods	Professor Lider Andrey Markovich
Three: Results and Discussion	Professor Lider Andrey Markovich.
Four: Financial management, resources efficiency and conservation	Associate professor Menshikova E.V.
Five: Social Responsibilities	Associate professor Verigin D. A.

Date of issuance of the assignment for Master Thesis completion according to the schedule	05.06.2021

Assignment issued by a scientific supervisor / advisor (if any):

Position	Full name	Academic degree, academic status	Signature	Date
Professor	Lider Andrey Markovich	PhD		

Assignment accepted for execution by a student:

Group	Full name	Signature	Date
0АМ9И	Ismail Omer Abubaker Omer		

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School of Nuclear Science & Engineering

Field of training (specialty): 14.04.02 Nuclear Science and Technology

Specialization: Nuclear Power Engineering

Level of education: Master degree program

Nuclear Fuel Cycle Division

Period of completion: spring semester 2020/2021 academic year

Form of presenting the work:

Master Thesis

SCHEDULED ASSESSMENT CALENDAR

for the Master Thesis completion

Deadline for completion of Master’s Graduation Thesis:	05.06.2021

Assessment date	**Title of section (module) / type of work (research)**	**Maximum score for the section (module)**
01.03.2020	Literature Review	
15.05.2020	Studying the Materials and Methods	
30.10.2020	Conduct experiments and receive results	
20.01.2021	Discuss and Analysis the output	
25.05.2021	Defense preparation	

COMPILED BY:

Scientific supervisor:

Position	**Full name**	**Academic degree, academic status**	**Signature**	**Date**
Professor	Lider Andrey Markovich	PhD		

APPROVED BY:

Program Director	**Full name**	**Academic degree, academic status**	**Signature**	**Date**
Nuclear Power Engineering	Vera V. Verkhoturova	PhD		

TASK FOR SECTION

«FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING»

To the student:

Group	**Full name**
0AM9И	Ismail Omer Abubaker Omer

School	Nuclear Science and Engineering	**Division**	Nuclear Fuel Cycle
Degree	Master	**Educational Program**	14.04.02 Nuclear physics and technologies

Input data to the section «Financial management, resource efficiency and resource saving»:	
Resource cost of scientific and technical research (STR): material and technical, energetic, financial and human	Salary costs – 231287.2 rubles STR budget – 264743.6 rubles
Expenditure rates and expenditure standards for resources	Electricity costs – 5.8 rub per 1 kW
Current tax system, tax rates, charges rates, discounting rates and interest rates	Labor tax – 27.1 %; Overhead costs – 30 %;
The list of subjects to study, design and develop:	
Assessment of commercial and innovative potential of STR	comparative analysis with other researches in this field;
Development of charter for scientific-research project	SWOT-analysis;
Scheduling of STR management process: structure and timeline, budget, risk management	calculation of working hours for project; creation of the time schedule of the project; calculation of scientific and technical research budget;
Resource efficiency	integral indicator of resource efficiency for the developed project.
A list of graphic material (with list of mandatory blueprints):	
Competitiveness analysis SWOT- analysis Gantt chart and budget of scientific research Assessment of resource, financial and economic efficiency of STR Potential risks	

Date of issue of the task for the section according to the schedule	

Task issued by adviser:

Position	**Full name**	**Scientific degree, rank**	**Signature**	**Date**
Associate professor	E.V. Menshikova	PhD		

The task was accepted by the student:

Group	**Full name**	**Signature**	**Date**
0AM9И	Ismail Omer Abubaker Omer		

Task for section
«Social responsibility»

To student:

Group	**Full name**
0AM9И	Ismail Omer Abubaker Omer

School	**Nuclear Science and Engineering**	**Department**	**Nuclear fuel cycle**
Degree	Master program	**Specialization**	Nuclear Power Engineering

Title of graduation thesis:

Mechanical and Adhesion Evaluation of SiC Coating on Zr-1Nb Substrates Prepared with Selective Laser Sintering Technique	
Initial data for section «Social Responsibility»:	
1. Information about object of investigation (matter, material, device, algorithm, procedure, workplace) and area of its application	Silicon-Carbide Coating on Zirconium alloy. Application area: nuclear fuel cladding in nuclear applications.
List of items to be investigated and to be developed:	
1. Legal and organizational issues to provide safety: Special (specific for operation of objects of investigation, designed workplace) legal rules of labor legislation; Organizational activities for layout of workplace.	Labour code of Russian Federation #197 from 30/12/2001 GOST 12.2.032-78 SSBT Sanitary Rules 2.2.2/2.4.1340-03. Hygienic requirements for PC and work with it Laser safety. General safety requirements for development and operation of laser products. GOST 31581-2012
2. Work Safety: 2.1. Analysis of identified harmful and dangerous factors 2.2. Justification of measures to reduce probability of harmful and dangerous factors	Enhanced electromagnetic radiation level Insufficient illumination of workplace Excessive noise Deviation of microclimate indicators Electric shock Laser radiation
3. Ecological safety:	Indicate impact of nuclear power plant on hydrosphere, atmosphere and lithosphere
4. Safety in emergency situations:	Fire safety;
Assignment date for section according to schedule	

The task was issued by consultant:

Position	**Full name**	**Scientific degree, rank**	**Signature**	**date**
Associate Professor Division for Nuclear-Fuel Cycle School of Nuclear Science & Engineering	Verigin D.A.	Cand.of Sc.		

The task was accepted by the student:

Group	**Full name**	**Signature**	**date**
0AM9И	Ismail Omer Abubaker Omer		

Abstract

This is a master's thesis work contains of 117 pages with 24 figures; 27 tables and 90 references.

Keywords: Scratch adhesion, micro-indentation, Silicon Carbide (SiC), elective Laser sintering (SLS), and Fuel Cladding material.

The main goal of this research is to propose most cheaper and accurate means of monitoring defects in SiC coatings on Zr-1Nb alloy substrates for nuclear fuel cladding studies. SiC micro-composites were deposited on Zr-1Nb alloy substrates at 200 µm thick for mechanical and scratch adhesion evaluations towards fuel cladding studies. Micro Indentation results proves SiC coated Zr-alloy having greater hardness as well as higher indentation elastic moduli compared to that of uncoated Zr-alloy which manifested in the lower depth penetration of the coating. Macro scratch adhesion reults of both coating variants yielded excellent adhesibility as wells as reasonable depth penetrated by the stylus of about 25 µm. Tribological results of SiC coated in air yielded friction coefficient a little above that coated in Ar atmosphere. Therefore, these results partially established SiC coatings a promising material for further studies.

List of Abbreviation

ATF	Accident tolerant fuel
BWR	Boiling water reactor
CRT	Cathode ray tube
HCP	Hexagonal close packed
LMS	Laser micro sintering
LOCA	Loss of coolant accident
LWR	Light water reactor
NPPs	Nuclear power plants
SCT	Surface coating technology
SEM	Scan electron microscope
SiC	Silicon carbide
SLS	Selective laser sintering
XRD	X-ray differaction
Zr	Zirconium

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Introduction

The silicon carbide has enabled strong mechanical properties due to its chemical composition [1]. The most suitable semiconductor has been announced for the electrical applications [2]. It contained the two different alpha and beta phases, which are synthesized in cubic, hexagonal, and rhombohedral crystal structures. Furthermore, the hexagonal structure has been sub-divided into 2H, 4H, and 6H type of structures. In more contrast, the stability of 2H is the most unstable while 4H type of structure has the lowest energy. However, alpha powder microstructure has a 6H co-axial grain that has lesser sintering capability than beta powder and requires higher temperatures for sintering. Consequently, beta phase contained co-axial fine grains, which can be converted to an alpha phase. Rather, if heated at above 1950°C, and forms a plate-shaped blade and will strengthen the silicon carbide in the case of coarsening**.**

As instance, in nuclear fission reactors the Zirconium alloys are constitutive materials. The wide detailed study of zirconium alloys microstructure and mechanical properties, which are affected by radiation throughout useful life, is essential either for security reasons. The radiation effect is most likely affecting mechanical behavior is irradiation hardening. The degree of embrittlement of irradiated components has to be determined. They zirconium alloys are more precisely a hydrogen source, which enters the zirconium alloy through an oxidation-hydriding combined mechanism. The hydrogen is generated by cathodic charge during corrosion of fuel elements cladding and by coolant radiolysis [3].

However, there are still several issues to be clarification purposes that in a radioactive environment that combines precipitated hydrides hydrogen in solution and the defects created by irradiation. In the core of a power reactor radiation damage as well as the hydrogen entry occur simultaneously, affecting the mechanical properties. Neutron irradiation that is generated within the reactor forms defects which eventually acting as barriers to the movement of dislocations, increasing the mechanical strength, and a loss the ductility.

On the other hand, a surface coating technology (SCT) defined as the alteration of the surface properties of bulk materials and imparting advances and unique functions to engineering components underneath coatings, such as excellent corrosion resistance, improved biological performance, and special magnetic or electrical properties of the materials [1-4]. It is noteworthy, that the performance and reliability of coatings depend on the mechanical properties of the material surface and its nature. The coating/substrate systems, i.e., the adhesion of coatings to their substrates. Other way around, the adhesion is a significant property for coating or substrate system that determines the durability and longevity of the completely testified system. With delamination or spallation of coatings on the surface, the components underneath will be directly exposed to environmental factors such as corrosive gases or liquids, abrasive particles, and high temperature, causing the components to function improperly and even to fail prematurely [5-7]. Therefore, the necessity to evaluate the coating adhesion with simple and reliable methods.

The mechanisms of coating adhesion are categorized as follows:

(a) Interfacial adhesion in which the adhesive forces are centered on a well-defined thin interface;

(b) Inter-diffusion adhesion in which the coating and the substrate diffuse into one another with a thicker interfacial region;

(c) Intermediate layer adhesion in which the coating and the substrate are separated by one or more layers of materials of different chemical compositions;

(d) Mechanical interlocking adhesion in which the coating/substrate interface is relatively rough [8]. The interdiffusion adhesion and mechanical interlocking adhesion are explicitly and usually exhibit relatively high strength. In addition, the adhesion strength of a coating to a substrate is also a function of many other variables such as the thermal and elastic mismatch between the coating and the substrate, the thickness of the coating, and the presence of defects at or near the interface [9-11]. To quantify the effects of these variables on coating adhesion, a good understanding of the adhesion and damage mechanisms of coating/substrate systems is of advantage. To achieve the full potential of coatings, it is necessary to develop reliable techniques for evaluating coating adhesion.

In the most recent years, a numerous method has been proposed and developed to characterize the adhesion of coatings to the substrate in open literature [5-8]. These methods more significantly be categorized into nucleation methods, mechanical methods, and miscellaneous techniques [5-6]. In more contrast the nucleation methods are based on the observation of the formation kinetics of films or coatings, and the early stages of coating formation are monitored. The above methods cannot be easily used to test the adhesion of coatings on practical tools or machine parts. In more detailed processes, mechanical methods are of practical interest and used widely in engineering and research [7-8]. According to the types of specimens, mechanical methods can be broadly classified into sandwich specimen-based and bimaterial specimen-based methods. Furthermore, a sandwich type of specimen is built up by sandwiching the coating into the test structure, while a biomaterial specimen includes only two types of materials: coating and substrate. The combined miscellaneous technical process could be referring to the measurement, which are still in a state of infancy but offer great potential, such as the thermal method, X-ray method, and capacitance method [5-6].

The above literature review is focused based on mechanical methods which are used for adhesion evaluation of coatings, along with emphasis on the principles, merits, limitations, typical applications, and recent improvements of each method.

Goals and Tasks of the Research

The main purpose of this research work is to develop the various technologies around silicon carbides to make it more acceptable as cladding material for the next generation of nuclear reactors. From the numerous discussions below, silicon carbide has some special properties that can be comparable above the existing fuel cladding material, which is zirconium. Despite zirconium-based alloys has gain recognition over its predecessor stainless steel from the first generation of reactors to the third generations, improvements need to be done through research and development to welcome the third generation plus and the fourth generation of nuclear reactors. There are so many ongoing research and development towards the generation (IV) reactors in which the nuclear fuel cladding material is one of the central concern due to the operational conditions of these reactors. There are three main categories of tasks associated with the research as stated below;

Goals

To investigate for the compatibility of the adhesiveness of SiC coat on Zr-1Nb substrate with the technique (SLS) used.

Tasks

1. Theoretical and practical Understanding of the coating technique.
2. Conducting the mechanical evaluations of the samples
3. Investigating the adhesive compatibilities of the sample
4. Analyzing and drawing conclusions on the experimental outcomes.

Chapter 1 - Literature Review

1.1 Silicon carbide (SiC)

In recent years, Silicon Carbide (SiC) has become increasing a more important material due to its refractive-ness, relatively high frequency and enormous power device application because of its comparatively superior material properties concerning the mechanical, electrical and chemical properties. SiC possesses low density, relatively high elastic modulus and low thermal expansion compared to ferrous metals (stainless steels). In terms of its electrical properties, it shows a high operation temperature, high thermal conductivity, high breakdown electric field with wide band gaps and saturated electron drift velocity compared to frequently used semiconductors such as silicon and gallium arsenide. The superior properties of SiC made it ideal for their application in micro and Nano-electromechanical systems (MEMS and NEMS) applications such as in aerospace technology, automobile industries and electrical and semiconductor industries [9-11].

These properties of the SiC are present in over 250 crystalline structures with stable crystallographic forms [12]. Some of these crystalline structures include 3C, 4H, 6H, 15R and 9T. 3C commonly known to be β-SiC with zinc-blended structure forms below 1700 °C whilst those formed above temperatures of 1700 °C are known as α-SiC with widely occurring polymorph 2 with hexagonal crystal structure. Figure 1.1 below illustrates the chemical structure of β-SiC [13].

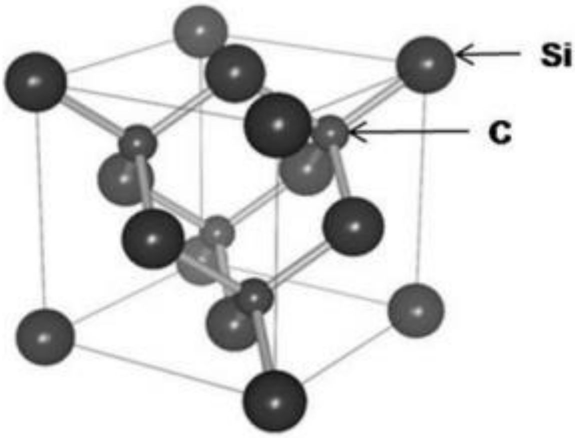


Figure 1.1 – chemical structure of β-SiC.

Phase transformation from β-SiC to α-SiC is possible via extensive heating above 2000 °C. Doping β-SiC with Boron transforms to 4H polytype α-SiC at relatively low temperature whilst nitrogen doped β-SiC also stabilizes the its transformation to 6H polytype α-SiC without the formation of 4H polytype. This transformation is reversible under pure nitrogen atmosphere. It is able to form a more form stable β-SiC phase up to 2500 °C by introducing nitrogen pressure. SiC bonds are not broken under atmospheric pressure but rather sublimation and dissociation of the compound into silicon and carbon occurs [14-16].

SiC in its natural form is colorless but the dark, gray, brown or black color of commercial SiC is a defect due to impurities such as iron. The theoretical density of pure β-SiC is 3.210 g/cm3 and that of pure α-SiC is 3.208 g/cm3, similar to lightweight covalently bonded ceramics. Experimental measurements reported the density of SiC in the range of from 3.166 to 3.249 3 g/cm3 depending on the polytype [15]. SiC possesses high hardness (HV10 > 2200 GPa), high Young's modulus (> 400 GPa), high thermal conductivity (120 – 200 W/mK), very low thermal expansion (3.6 – 4.1 x 10-6 /K at 20 to 400 °C), high thermal stability, high resistance to corrosion, abrasion and erosion, and also toxicologically safe [16]. SiC is resistant to any acidic, alkaline, or molten salts up to 800 °C. In air, SiC forms a protective silicon oxide film at 1200 °C and is capable of being used up to 1600 °C. The high thermal conductivity coupled with low thermal expansion and high strength make this material excellent thermal shock resistance. Table 1.1 below, lists some of the properties of α-SiC compared to the most commonly used materials: aluminum 6061 and stainless steel 316. Similar to all other ceramics SiC is brittle. However, many efforts have been made to produce fiber-reinforced SiC composites that have shown promising impact strength for wide applications.

Table 1.1 – Comparison of material properties.

Material	Density (kg/m3)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Melting Temp. (°C)	Thermal Cond. (W/m·K)	Linear Thermal Expansion Coefficient (10-6 K-1)
α-SiC	3.1	>400	550	550	120	2.77
Al 6061	2.7	65 – 70	240	550 - 650	150 – 210	23.1
Stainless Steel 316	8.0	193	>750	1400	16.3	15 - 18

The optical absorption of SiC is characterized by intra-band and inter-band absorption components. The absorption coefficient of SiC is reported to range from 10 – 5.5 × 104 cm-1 in the energy range between 2.42 and 4.4 eV. The band-gap of β-SiC is in the range of from 2.13 to 2.32 eV. The transmission and reflectance rate of β-SiC as a function of wavelength are shown in Figure 1.2. It is observed that, β-SiC becomes almost transparent to the light with wavelength of above 500 nm [17-20].

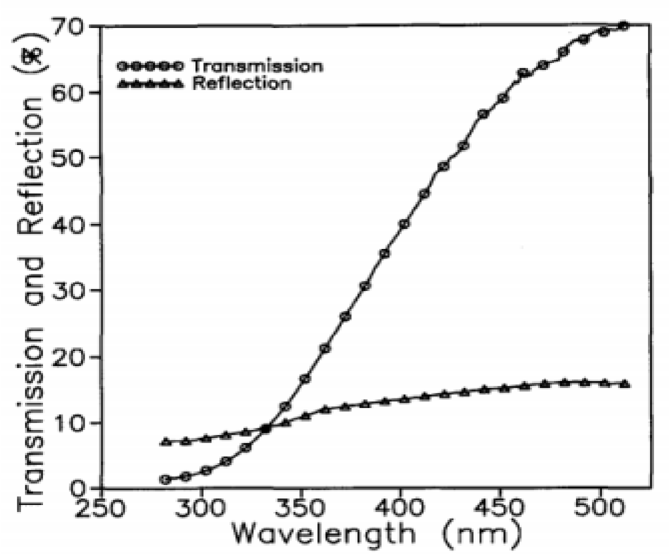


Figure 1.2 – Transmission & reflection rate of β-SiC film.

1.1.1 Chemical Composition of Silicon Carbide

The formation of SiC is from a mixture of SiO_2 and some form of carbon low in ash. The chemical reaction is expressed in the form [13-16]:

$$\text{For } SiO_2 + 3C = SiC + 2CO \qquad (1.1)$$

The synthesis of β-SiC in the form of gaseous intermediate SiO takes place in the following sequence starting with the important reactions first;

$$SiO_2 + C = SiO + CO \qquad (1.2)$$

$$SiO_2 + CO = SiO + CO_2 \qquad (1.3)$$

$$SiO_2 + CO = SiO + CO_2 \qquad (1.4)$$

$$C + CO_2 = 2CO \qquad (1.5)$$

$$2C + SiO = SiC + CO \qquad (1.6)$$

SiO is initially formed at the contact points of the carbon and SiO_2 formed from the reaction in equation (1.2). High portion of SiO are generated which indicates that the gas/solid mechanism through the reactions in equations (1.3) and (1.4) is the one, which makes the reaction in equation (1.5) possible once the C and SiO2 contact points are consumed. The initial carbon source has a substantial influence on the product of

SiC morphology and the rate of the reaction: finer carbon crystallites react faster than larger ones due to the surface area [21]. SiO_2 crystals have little influence on the reaction rate. SiC is then sintered with all 6 crystallographic orientations;

Low temperature enables the formation of beta-silicon, with a simple cubic crystal structure whilst higher temperatures results in one or more hexagonal close packing crystal (HCP) structures. These modifications, which differ only by the position of the atomic layers referred as to α-SiC. The fabrication of SiC with specified shape as in the form of Si-SiC composite made by the reaction-sintering or reaction-bonding process. During the process, SiC powders are mixed with carbon in various forms and the mixture heated in the contact with molten silicon in its pure state. The term reaction sintering is from the reaction between carbon and silicon to form SiC. The carbon used in the process is transformed into the new SiC bonds to the original particles [13]. Ruff concluded that this reaction begins above temperatures of 1500 ºC and under the condition of his experiment, completing at 1800 ºC [22]. Recent, findings from numerous experiments have conducted with a different reaction:

$$Si + C = SiC \tag{1.7}$$

In using pure silicon and carbon to form SiC based from the above equation, SiC is only formed when the melting point of silicon (1430 ºC) is reached. The reaction temperature can be as low as 1000 ºC if using nickel-silicon or aluminum-silicon alloys instead of pure silicon. Taylor and Laidlor reported the formation of SiC at 1150 ºC when some alloying agent reduces the liquefying point of silicon below 1400 ºC [15-16]. Antipin and Ivanson reported beta-SiC can be formed from the electrolytic production of a silicon-aluminum alloy liquid at 1000 ºC in graphite crucibles [23].

1.1.2 Silicon Carbide Sintering

For materials with predominantly covalent bonds, sintering of SiC is considered not to be possible in the absence of additives [24-25]. The conventional fabrication of ceramics overwhelmingly involves a heat treatment process known as sintering, where the powder material is bonded and formed into a desired shape and then, is converted into a dense solid. There are four categories of application for sintering of SiC: (1) solid-state sintering; (2) liquid-phase sintering; (3) vitrification; and (4) viscous sintering. In some cases, where high density and fine grain size are required, a process called Pressure, sintering can achieve full densification by applying external pressure during heating.

1.1.3 Solid-State Sintering

In solid state sintering, the pre-shaped body is heated to a temperature typically between 0.5 – 0.9 of the melting point of the ceramic material. No liquid phase exists during the process and atomic diffusion in the solid state leads to joining of the particles and reduction of the porosity. Coble identifies three stages occurring simultaneously during solid state sintering [26]. The initial stage was characterized by neck growth among particles as well as shrinkage. Because densification mechanisms is the dominant phase, no grain growth occurs during this stage. During intermediate stage, grain starts to grow and the pore surfaces become intersected by grain boundaries. The pore phase continues to shrink until the end of the intermediate stage. During the final stage, discontinued grain growth moves the grain boundaries away from the pores and thus, further enhance the grain 8 boundary diffusion [27-29]. Several models have been introduced in trying to understand these mechanisms which occur during solid state sintering, including the neck growth, surface and grain boundary diffusion, pore phase, transport mechanism, etc. [30].

1.1.4 Liquid Phase Sintering

In liquid phase sintering, only a small volume of the powder mixture is converted into liquid at the specified sintering temperature. The liquid then flows and fills the pores under the influence of capillary forces. Even though the liquid volume is insufficient to fill all the pore space to achieve full densification, the rate of inter-particle bonding is enhanced during the process. Consequently, significant improvements are usually accompanied with liquid phase sintering, which include increased densification rate, accelerated grain growth, or producing specific grain boundary properties. The distribution of the liquid and the resulting hetero-phases after densification plays a crucial role to the properties of the sintered body. However, the proper control of the composition of the liquid is extremely difficult due to the small amount of liquid volume [31].

1.1.5 Vitrification sintering

It is akin to liquid phase sintering in that, the process has a relatively large volume of liquid, typically more than 25% of the volume is formed, which is sufficient to fill the pore space for complete densification. Crystallization or vitrification of the liquid upon cooling can be expected. For viscous sintering, when ceramic particles are heated-up close to the softening temperature, viscous flow by surface tension leads to densification of the powders [13].

1.1.6 Sintering Additives

Densification of SiC without hot pressing is not possible in the absence of sintering aids [32]. Sintering additives such as boron, aluminum, carbon, etc. are commonly used in the amounts of a few tenths of a percentage. Boron and carbon additives are known to promote sintering by a solid-state processing. SiC powders doped with boron and carbon show remarkable shrinkage in the early stages, indicating that the densification occurs by grain boundary diffusion. Boron is known to activate the sintering process by facilitating the formation of a liquid phase of Si-B-C system eliminating porosity among particles. Doping with boron without carbon yields a fine microstructure with small shrinkage. [33]. Also, the presence of excessive carbon can prevent oxidation of SiC by removing the native SiO2 layer during sintering, which can drastically increase the self-diffusion rate. Carbon can also react with any excessive silicon present or formed during sintering, then subsequently yields densification of SiC [34]. Aluminum and boron both act as acceptors in SiC. Aluminum may inhibit matter transport along the boundary. Additionally, aluminum is known to promote the transition from β-SiC to α-SiC, stabilizing the 4H 10 polytype and enhancing basal growth. This indicates that aluminum may promote the evolution of a more homogeneous microstructure than those of SiC sintered with boron and carbon only. Furthermore, when aluminum is combined with boron and carbon, it is able to restrict excessive grain growth of α-SiC, lower the sintering temperature, and increase the final density of the sintered part. Metal oxides such as yttrium and aluminum oxides have also been successfully used as additives for SiC sintering. Their presence is presumed to be mainly promoting liquid phase sintering. Therefore, liquid phase sintering of SiC can further reduce the sintering temperature by the use of metal oxides and the most promising additives are Al2O3, Y2O3, and MgO, which can accelerate the formation of melt and sintering without reacting with SiC. Long sintering time of typically a few hours allows the diffusion of Y, Al, and Mg from the oxide melt into SiC grains. These metal oxides are known to have no effect to the thickness of the boundary layer on the grains. Under the surface tension and capillary force, the formed liquid spreads over the surface, wetting and filling the pores among SiC particles. Consequently, the microstructure of liquid-phase sintered SiC part normally has SiC grains bonded by oxide phase. Various combinations of these sintering additives such as silicon, boron, carbon, aluminum, metal oxides, etc. have been tested and compared by numerous researchers for producing near full-density SiC parts. Many ceramic sintering processes involve a certain degree of reaction. Sacks developed a transient viscous sintering process for SiC, which involves rapid viscous densification of powders due to viscous flow of the amorphous SiO_2 layer on the particles. A subsequent reaction produces fully densified mullets (Al6Si2O13) – SiC composite [35-38].

As mentioned above, SiC is formed from the reaction between pure silicon and carbon at as low as at the melting temperature of silicon at 1430 °C. Liquid silicon is driven by capillary force into pores of the solid carbon matrix, where it reacts with the pore walls to form SiC. [39]. This process has also been used to produce reaction bonded silicon carbide (RBSiC), with liquid silicon which rises to wet and fills the pores while reacting with carbonized binders to form additional β-SiC [40]. Note that, some processes require hot-press sintering mainly due to lack of liquid phase [41].

1.1.7 Reaction Sintering

Reaction sintering is another type of sintering process where new phases or crystals are formed during heating. Sacks developed a transient viscous sintering process for SiC, which involves rapid viscous densification of powders due to viscous flow of the amorphous SiO_2 layer on the particles. Other reactions leads to fully densified mullites (Al6Si2O13) – SiC composite [42]. As mentioned above, SiC is also formed from the reaction between pure silicon and carbon with as low as at the melting point of silicon at 1430 °C. Liquid silicon occurs by capillary action into pores of the solid carbon matrix, and then reacts with the pore walls to the SiC structure [43]. This process has also been used to produce reaction bonded silicon carbide (RBSiC), where liquid silicon rises to wet and fill the pores while reacting with carbonized binders to form additional β-SiC [44].

1.2 Selective Laser Sintering

Selective laser sintering (SLS) is a technique, which involves the use of additive manufacturing technology that uses laser to selectively sinter powder materials layer by layer in order to form a solid mass of 3D structure. It was developed and patented by Dr. Joseph Beaman and Dr. Carl Deckard of the University of Texas at Austin in 1980s [24-36]. SLS technology has been widely used in industry because of its capability to produce 3D complex-structure parts directly from the CAD model. In addition, compared to other additive manufacturing techniques, such as stereo-lithography (SLA) and fused deposition modeling (FDM), SLS process requires no supporting materials because the sintered part is surrounded and supported by un-sintered powder at all times, which allows for the construction of more 14 complex 3D structures. SLS process is capable of producing parts made from a wide variety of materials, including polymers, glasses, ceramics, and metals for rapid prototyping, and even rapid manufacturing of final products [45]. The creation of complex geometries of SiC parts is possible, but with difficulties. It is possible to use indirect SLS methods to create SiC preforms from a powder mixture of SiC as structural material and with thermosetting polymers as binder material. These parts are further processed at elevated temperatures to carbonize the polymer binders followed by reactive infiltration of silicon to yield near-net shape parts [28-39]. It is also possible to introduce the application of transient binders to infiltrate SLS-process polymer-SiC preforms in order to prevent shrinkage and collapse of the structure between softening and cross-linking of the initial polymer binders. This allows for support-free infiltration of SiC preforms with minimal deformation and shrinkage of the parts during the furnace sintering [30-41].

Regenfuss and Exner introduced laser micro sintering (LMS) in 2002, which is a modification of SLS process. This has been successfully employed in the creation of metallic micro parts. It involves the application of high-frequency pulsed laser, new powder and slurry coating system, and the proprietary CAD software [46]. This technology has also been used to process non-metal materials, including oxide and non-oxide ceramics [47]

1.3 Possible adhesion tests for coating materials

Metallic reinforced ceramic coating has undergone decades of improvement to suit their applications. The metal-ceramic coating interfaces are very important in many applications such as in designing ceramic devices, structural composites, environmental coating as well as cladding materials which is defines the main theme of this research. This category of materials is employed in the industries based on the several inherent advantages such as the ability to withstand high thermal conditions, their outstanding optical and electrical properties as well as the resistance to chemicals and environmental degradation. However, the basic focus throws more light on the properties of the interface based on adhesiveness, interface structures, chemistry and mechanical characteristics [38-46].

In order to guarantee an excellent coating of material, it is absolutely necessary to conduct the various adhesion tests on a sample on the test piece to ensure a perfect adhesion attachment between the coating material and the substrate material. There are several variations of such adhesion methods to determine how well the coating is bonded to the substrate. Records are needed to be taken after each level of test in order to think over the adhesive bond whether it is below, intermediate or at higher standards. This will also be used to detect if the bond failure was adhesive, meaning there is failure on the substrate interface, or cohesive, meaning there is failure within the coating material itself or the substrate. Various adhesive tests are discussed below.

1.3.1 The adhesion knife test

The knife test is one of the simplest adhesion testing technique since it is common to find knife at any moment. This technique is able to give an information based on how difficult it takes to take off a coating. The procedure involved is actually centered on the degree of tilt at which the knife penetrates the coating. Using a knife tilted at angle between 30 to 45 degrees to initiate two cuts between the legs and down towards the substrate, which intercepts to form an X crosscut within. An attempt is then made in order to lift the coating using the pointed side of the knife from the vertex. Due to the nature of the test, it is highly advisable to involve an experience inspector in analyzing the result of test in the process. However, a high degree of cohesiveness may inversely affect the adhesion than one, which is brittle and may result to easy fracturing when investigated thoroughly [48].

1.3.2 Adhesion Tape Test

This adhesion test method involves the use of pressure-sensitive tapes over coating films to a material and then removing the tape over the cut zone made in the film. If a coating’s aim is to fulfil a desire function of protecting, strengthening and decorating, then it must adhere firmly to the substrate involved. In order to conduct tape test to know the level of adhesion of the coating to the substrate, an X-cut is made on the coating film through to the substrate. This is then followed by the application of the pressure-sensitive tape on the cut zone and then the tape can be removed to assess qualitatively the adhesion capability based on a scale of range from 0 to 5. This style of adhesion testing can be highly used in the field or job sites in assessing this property [49]. The figure 1.3 below gives a general view on how the incisions are done under the tape testing technique.

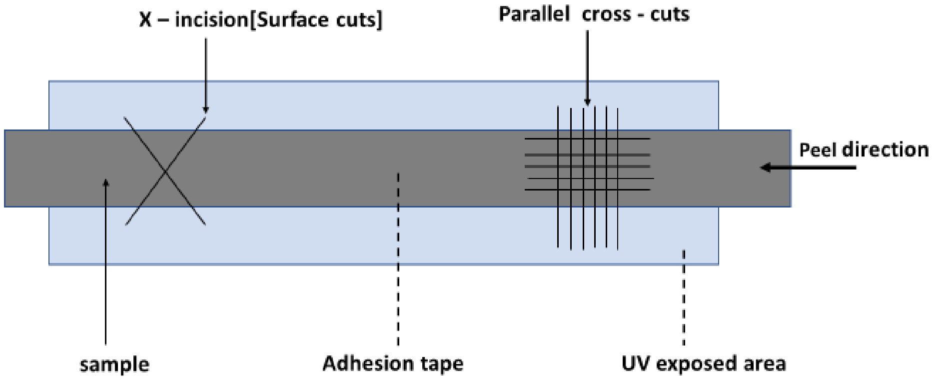


Figure 1.3 – Coated sample with an ‘X’ and parallel cuts prepared for tape testing.

Another method under the tape adhesive testing method involves creating a lattice pattern of about six to eleven cuts on the film through to the substrate. This is then followed by erecting a pressure-sensitive tape over the cut regions and the tape is then removed. The level of adhesion is then evaluated through comparing with descriptions and illustrations [50-51]. This tape category is mainly suitable for laboratory adhesion testing of coating materials. However, this technique is not suitable for film thickness greater than 5 Mils or 125μm equivalence. Moreover, this is just a general technique of adhesion testing to check for establishing a general adequate level, because it is not able to distinguish between higher levels of adhesion. To assess a higher level of adhesion of very important coating material, it is required that a more sophisticated approaches are used in measurement of this property [52]. The main cutting tools for this assignment includes the sharp razor blades, knife, scalpel and equivalent cutting edges in very good condition. The cutting tools are supposed to be straight and tough, therefore, it is advisable that these cutting tools are made of steel and other hardened metals in order to avoid bending. More also, a pressure-sensitive tape of reasonable thickness is required for the job.

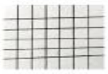
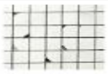
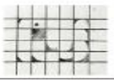
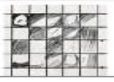
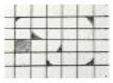
a. Procedure for the adhesion tape test

First of all, a portion of the test piece is selected and it should be free of any kind of flaw that is visible on the coating material. It should be mandatory that the surface of the coated material is well smoothened, cleaned and kept dry. This is because; extreme temperatures and humidity might affect the adhesion of the tape on the coating.

An X-shape is created on the film of the test piece with a suitable depth depending on the thickness of the coating on the substrate. This is done at an angle of between 30 to 45 degrees. In the process of incisions, the straightedge should be focused on cutting through the coating to the substrate in a steady motion. The incisions ought to be inspected using a light reflecting on the surface of the metal to establish that the penetration of the coating film is being established. Before the testing is conducted, it is required to discard completely at least two laps of the pressure sensitive tape from the roll. An additional length of calculated length is removed and then cut from the piece.

At this point, the central portion of the pressure-sensitive tape is placed on the intersected portion of the X shape incisions and the entire roll of tape is run on the cut. A rubber coated roller is used in rubbing uniformly the tape on the test piece. The removal of the tape is done within a time interval of about 90 ± 30 seconds after application. The tape can now be removed by seizing the free end and pulling it off rapidly back on itself at 180 degrees. In this stage, inspection can now be conducted on the X-cut zone where comparison is made with the appearance of the taped zone and the original coating and rated using the scale in the table 1.2 below.

Table 1.2 – Scheme guide to evaluating an adhesion test.

Classification	Area covered after removal [%]	Flaking view from cuts after removal of tape [%]
5B	0 %	
4B	< 5 %	
3B	5 – 25 %	 
2B	25 – 35 %	 
1B	35 – 70 %	 
0B	> 70 %	 

At this stage, the test should be repeated at two other locations on the test piece to establish a concrete authenticity on the coating interface. However, several test should be repeatedly done on large structures to establish a full assessment on the adhesion distribution all over the surface. Lastly, the innovative needs to be cleaned and abraded lightly with a fine oil sharpening stone before engaged in any operation. However, all cutting tools that exhibit nicks and some defects after the testing should be discarded so as not to affect the results of any future testing. After the test is evaluated, a comprehensive report needs to be written in order to analyze the outcome of the test and conclusions made based on adhesion ability of the investigated material. The table below describes and gives the necessary information that is required from the evaluated results as obtained from the test, which needs to be filled, analyzed, and conclusions drawn.

1.3.3 Peel Adhesion test

Peel adhesion test is a method that involves the sticking of pressure-sensitive adhesive to measure the bonding strength of this adhesive to a mating substrate. Adhesives such as bandages, label and masking tapes used in painting were some of the earlier applications of adhesives in order to evaluate how easily and difficult it takes for them to be ripped off on applied surfaces. Hence, these earlier applications paves ways for the discovery of the method as a suitable means to investigate for the adhesion properties of coating substrate and material interfaces [53].

Peel adhesion can be defined as the force required to peel off an adhesion item from any given surfaces regardless of the nature of the material interface. During the process of peel test, the peel force P is measured with a pressure-sensitive tape of film of dimensions of a few millimeters wide. This peeling is done carefully and steadily with a peel adhesion tester machine as depicted in the figure 1.4 below.

Figure 1.4 – 90^0 Peel adhesion tester machine [43].

In this system, a calculated amount of the pressure-sensitive tape is laid perfectly on the test-piece and the remaining part of the tape is clamped to the system. The peel adhesion tester system adjusts automatically the exact force that is suitable to performed the peeling and this is done at angle of 90^0 depending on the angle specification of the machine used. However, this test can also be done alternatively by calculating the rate of energy involved in pulling which is also a direct measure of the adhesive strength of the coating established by using the equation 1.1 below[86].

$$G = \frac{P}{b}\,(1 - \cos \theta) + \frac{P^2}{2b^2 Eh} \tag{1.8}$$

From the equation 1, the peeling angle is represented by $\theta,$ where b and h represent the tape's width and thickness respectively. The Young's modulus of elasticity of the film is denoted by E. Performing this test under similar standard conditions yields same repeatable results. Major part of the energy dissipated during the process erupts from the tensile and bending forces from the film and adhesive overlayer which collectively yields a huge amount of plasticity. However, the test results are also influenced based on strength of the film and the adhesion of the tape. Therefore, this method of adhesion testing should be limited to only systems that poses relatively poor adhesion properties.

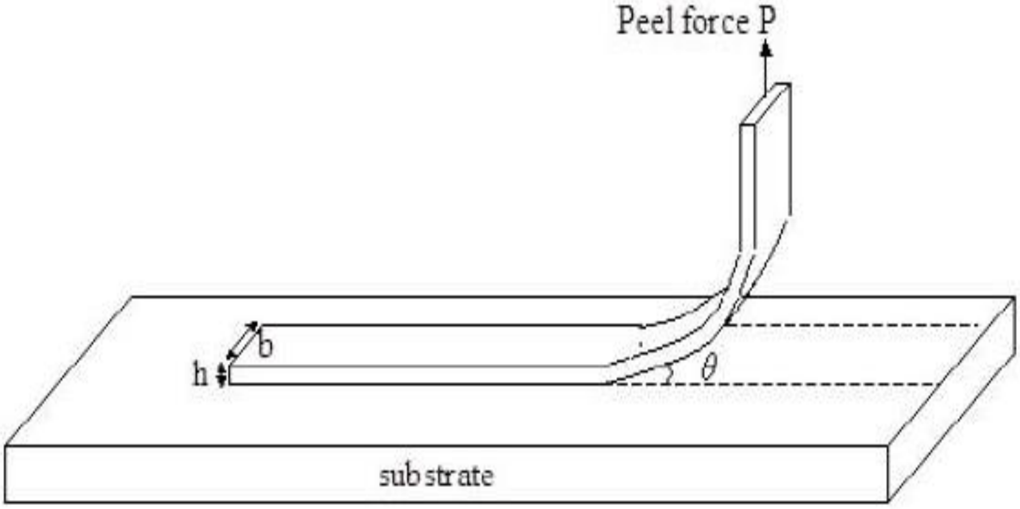


Figure 1.5 – Scheme of the peel test

However, one main advantages of the peel test are extremely low cost of the sample preparation and the simplicity involved. An added advantage is also the ability to control precisely the rate of delamination. A disadvantage of the technique has to do with the relation existing between the qualitative value of the peel force *P* and the strength of the coating and substrate interface is highly dependent on the peeling angle as well as the plastic dissipation during the propagation of cracks [54].

1.3.4 Scratch Adhesion Test

This is an adhesion testing technique that utilizes smooth rounded stylus usually of diamond, which is scratched across the surface of the film material. In the process, a vertical load is exerted on the stylus and the magnitude is gradually increased until a critical value is reached where the film starts to strip deep on the surface of the substrate material which leaves a distinct mark on it. At this stage, a microscope can be used to view the stripping of the film whiles, the critical load is measured through characteristic acoustic emission.

An important aspect of the technique is being able to measure the minimum critical load P_{cr} at which the delamination takes place and this value can be used in computing the practical work of adhesion $W_{A.P}$. The equation 1.2 below shows the relationship existing between the minimum critical load $P_{cr,}$ and the practical work of adhesion $W_{A.P}$ [55].

$$p_{Cr} = \frac{\pi r^2}{2}\left(\frac{2EW_{A\cdot P}}{h}\right) \tag{1.9}$$

In the equation 2, the r represents the contact radius while h being the thickness of the film. However, this analysis is necessary only when the compressive load is normal to the film. The difficulty lies in analyzing the mechanics pertaining to this system of adhesion testing and to link the critical load to the film adhesion. In order to successfully compute the energy involved in the adhesion test, the mechanical properties of films and substrate, film thickness, the rate of loading and the sharpness of the stylus coupled with the scratch elastic stress distribution are needed to be well noted, making the method stressful.

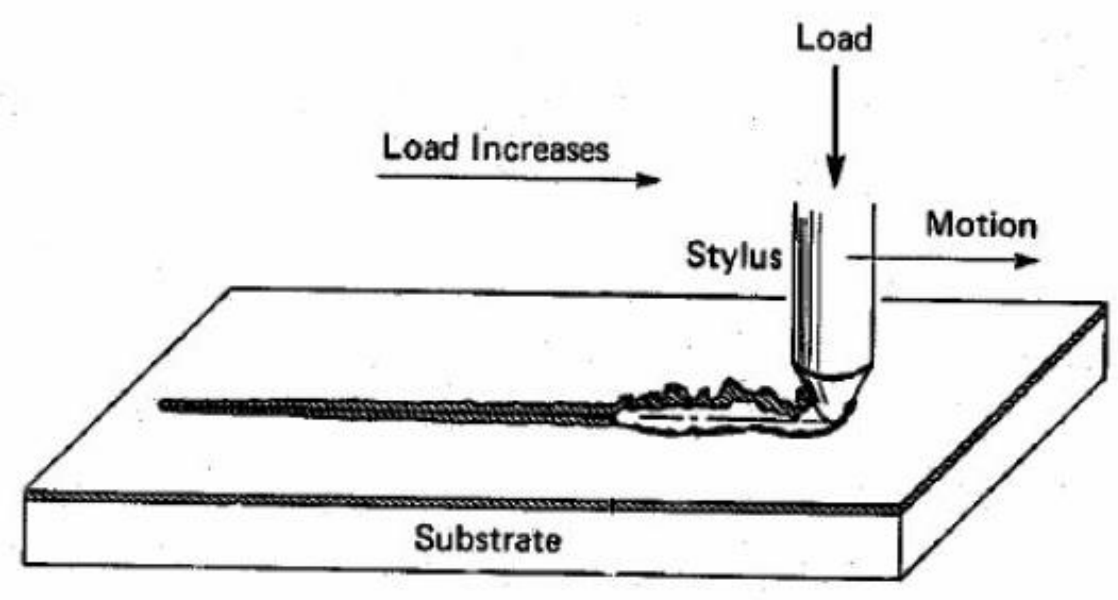


Figure 1.6 – Scheme of scratch adhesion testing.

Despite the complications involved in the analyzing the scratch adhesion testing, it still has several merits, such as the simplicity of sample preparations and there are no intrinsic limitations to the force. Therefore, debonding a tough substrate interface is even more possible. The figure 1.6 above gives a clearer view on how the scratch adhesion testing is conducted [56].

1.4 Mechanical Destructive analysis

Although destructive method seems to be harsh method of testing for a material, it is historically being the preferred method of testing method. It has also been largely the only way to gain accurate results. This method of testing has been in existence as long as humans discover the mixing and manufacturing metallic items. When these metals are broken down, it becomes easier to observe the makeup and compare it to other recognized materials to determine the structural composition of a specific item. In the course of the doing this, part of the item used during the process of testing will definitely be destroyed.

In instances of building, construction, and manufacturing industries where there are huge amounts of metal scrap left over, the method possesses a disadvantage of incurring lots of waste items and increases the budget of the industries involved due to inability to recycled some of the degree of waste items involved. Though it seems to be a weird method of testing, its history of testing metals destructively remained untraced, but it makes sense that the best way of finding out the composition of anything, that things needs to be disserted before it can be studied well. Despite the discoveries and inventions of non-destructive testing techniques, the destructive technique will still remain an important approach to obtaining accurate information of material composition in the mechanical evaluation of these materials.

1.4.1 The bending (flexural) test

This is a one of the categories of destructive testing method which provides the modulus of elasticity, flexural stress, flexural strain and the flexural stress strain response of a material under investigation. This technique can be applicable to any type of material with rectangular to circular shape with defined dimensions. Bending or flexure is a way of characterizing the behavior of materials subjected to an external load. The main aim of flexural test configuration is to define a material’s tendency to withstand deformation under load. Flexural strength which is also known as the modulus of rupture, bend strength or transverse rupture strength is a property of a material which determines stress in a material just before it yields in a flexure. In definition, a yield point on the stress-strain curve that indicates the limit of elastic behavior and the commencement of plastic behavior. Whereas, the yield strength is defined as the point of stress at which a material begins to deform plastically and the yield point is the exact point where nonlinear deformation starts [57-58].

There are two popular types of the bending tests namely; three-point bending and four-point bending tests. The figure 1.7 and 1.8 below illustrates the set-ups of the flexural tests. An object made of a single material such as steel rod and wooden beam when subjected finally by two supports explains simply how the three and four flexural test works as illustrated below.

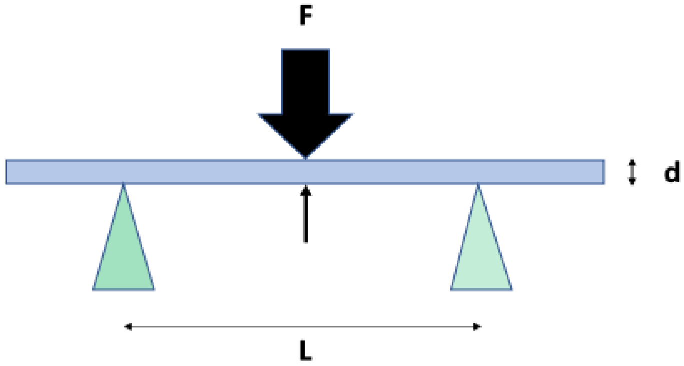


Figure 1.7 – Simplified scheme of the three-point bending test.

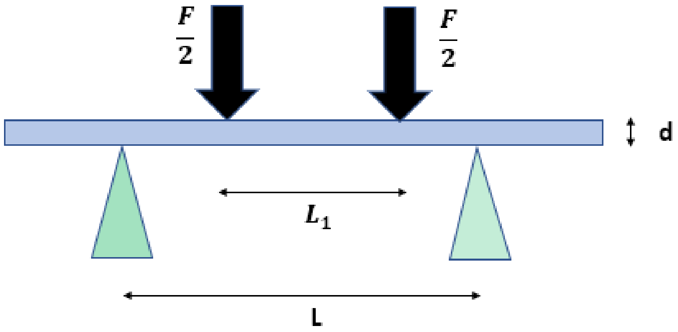


Figure 1.8 – Simplified scheme of the four-point bending test.

The figure 1.7 describes a typical three-point configuration and it takes into account the production of peak stress at the central portion of the sample material under investigation and thereby reducing stress elsewhere. Meanwhile, in the four-point bending test configuration, the subjected stress extends to a larger region of the material than the three-point configuration test and hence able to give a detail information when that material is subjected by larger body which covers a greater portion of the material and terminates pre-mature destruction. Considering a rectangular sample, the resultant stress as a result of axial force subjection can be obtained using the equation 1.10 below.

$$\sigma = \frac{F}{bd} \tag{1.10}$$

However, the equation 1 above cannot be relied on precisely in computing the exact stress due to lack of cross-sectional description of the sample into detail. However, the F represents the axial load at the point of fracture, the σ represents the flexural stress, b represents the breadth and the d represents the thickness of the sample. In figure 1.7, the sketch illustrates a *three-point* configuration during a bending test. The flexural stress can be computed using the equation (1.11) below.

$$\sigma = \frac{3FL}{2bd^2} \tag{1.11}$$

For the four-point bending set-up in figure 1.8 above, a lot is taken into account, making the equation 2 to undergo a substitution of necessary dimensions involved. The equation 1.12 is suitable for finding the flexural stress of a rectangular shaped or squared shaped sample.

$$\sigma = \frac{3F(L-L_i)}{2bd^2} \tag{1.12}$$

Moreover, a three-point flexural test is mainly applicable when the sample material is homogeneous such as a plastic material whiles a four-point flexural test is more suitable for materials with inhomogeneous composition, such as composites or woods. Also, it is easier to conduct a three-point flexural test than a four-point flexural test. In a three-point flexural test, a digital encoder is responsible for measuring the deflection whiles the four-point bend test is measured with a deflectometer [59]. The figure 1.9 below explains briefly the inherent characteristics of the flexural testing.

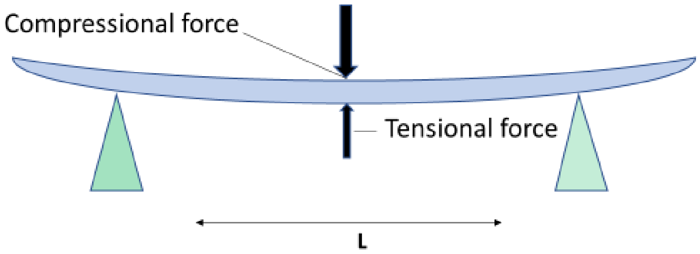


Figure 1.9 – A beam subjected to bending from a side and its consequence.

The concave face is as a result of the range of stress that the sample is exposed to, especially the exact internal of the bend which endures the maximum compressive stress effects. Meanwhile, the external part of the bend which forms a convex face shows a stress behavior of maximum tensile value. Hence, the arrows in the figure 1.9 points to the exact portion of extreme fibres. Moreover, some materials have a higher tendency to fail under tensile stress before giving up under compressive stress. Therefore, the maximum tensile stress that can be endured before the failure of the beam or rods is its flexural strength.

There exists some kind of relation between the flexural and the tensile strength. For instance, a homogeneous material's flexural strength could be the same as that of the tensile strength. However, many serves as the point where stress can concentrate to continuously weakened that zone as the magnitude of the force exerted increases, thereby, seems as a zone of extreme fibre and an exact point where the bending is initiated as well as breaking. In homogeneous materials with very smaller defects, the point of extreme fiber develops at where the force points directly, provided the material is under same stress and failure is initiated immediately when the weakest fibre approaches its limit of tensile stress. This then explain why it is common for flexural strength to exceed tensile strength for same material.

Alternatively, homogeneous materials with defects available on the surface only tends to have higher tensile strength than flexural strength and this is also based on the location of the defects. Considering all defect negligible, most materials are expected to fail under bending force which is lesser than the conforming tensile force and both forces contributes to the stress whose value depends largely on the strength of the material [60].

1.5 Hardness of materials

Hardness is the property of the material that resist the scratch on its surface. In other words, it defined as the resistance to indentation, that is determined by measurement of the permanent depth of the indentation. In an experimental work applying force on the material surface by a given indenter the smaller the indentation, deflect by the hardness of the material. The depth or the correctional area of the indentation using one of over 12 different test methods [22] measures indentation hardness. The necessity to categorized the hardness into following categories as:

1.5.1 Hardness testing

- ➢ Material Properties
- • The testing material
- • To check the hardness of the material
- • Following confirm process
- • Tensile strength of the material
- ➢ Functionality (Operations)
- • The confirmation the ability to design
- • To process of wear resistance
- • To check the toughness
- • Resistance to impact

1.5.2 The consideration of hardness testing

In the hardening test the following specimen and its characteristics should be considering for the selection of hardness testing process being used to selecting the hardness testing method to use:

- Testing material
- The parameter of the specimen (size)
- The thickness of the specimen
- The measuring unit (scale)

- The geometrical shape of specimen, might be (circular, cylindrical, flat, or irregular geometry

1.5.3 Important of Hardness Testing

For the consideration of the related information and the most significances in various sectors such as structural, aerospace, quality control, automotive, the analytical, and several other forms of industry and manufacturing. To determine these material properties, offer a positive impact that insight in terms of the strength, the flexibility, durability, and capabilities of a numerous types of components formed by the raw materials.

Even though the hardness test is an extensively process that used for the proper form of material tests. It is rather easy to perform and completely or minimally non-destructive, and that is almost inexpensive when compared to other types of material verification equipment. Therefore, the test could be typically taken out directly from the component without major changes. On the other hand, the testing techniques have been considerably improved the electronics and computer ages for and advancement that is previously techniques included simple scratch tests.

Initially the hardness tests based on a bar that increased in hardness end to end. The hardness at the level of the material being tested could produce a scratch on the bar. The scratch has to be considered as determining factor at the specimen hardness. For more fine results, the hardness testing comprised of scratching material surfaces with a diamond and measuring the width of the resultant line and, consequently, indentation of the material using a steel ball under force. It is seen at the increased manufacturing requirements brought about by the global industrialization, and then a much more urgent demand during both World Wars, more refined techniques and machines were developed [52-60].

The most efficient and accordance forms of testing are required for affective and in response of the structural failures, due to heavy manufacturing demands, and the specific need to design adequate material integrity into growing global infrastructure. The most recently, the importance and advances in electronics techniques, and software have led much more sophisticated hardness testing equipment. These tools are capable and considered as reliable, and with extreme useful and property critical information [61].

A most significant and commonly used definition is the resistance of a material to which is used to modify for permanent and plastic deformation. Whether another form of hardness testing in terms of electromagnetic, rebound and ultrasonic are employed in a wide range of applications. These properties are used to measure material hardness through indentation hardness testing offers simple, reliable, and a commonly understood test type. This test is measured by loading an indenter of specified geometry and properties of the material for a specified length of time. It is the depth and the penetration or dimensions dependents of the resulting impression. The depth of penetration of the indent dimensions should be larger as the material being tested is after.

The most common hardness testing varieties those are including Rockwell, Brinell, and Knoop/Vickers. In Rockwell testing that is the most widely used method for the quick results produced which is usually usable for alloys or metals. Knoop and Vickers testing are more ideal specially for coatings, thin materials, and mounted metallographic components. In comparison of those tests the Brinell testing applications normally include large steel framework, cast iron, and aluminum. Rather than the above testing, some of the hardening tests could be performed very quick by manual devices [62-63].

Moreover, the indent made by the hardness test that could be grounded or it could be small in size no effect to the performance or appearance of the component. Since the hardness testing is done to the component itself, each product or a spot check of products can be tested before shipping to the customer [64].

1.5.4 Common Types of Hardness Tests

In more contrast the Rockwell hardness test is based on an inverse relationship to the parametric and additional depth to which an indenter is forced by a heavy load. Initially, a minor load is applied for the establishment of a zero datum position. Which is followed by applying the major load for a specified period and it is then removed, leaving the minor load applied. The resulting Rockwell number represents the difference in depth from the zero-datum position as a result of the application of the major load. The whole procedure needs as less time which is up to fifteen seconds for plasticity [25].

In more detailed the Rockwell test, results are rapidly and directly obtained without the need for a secondary, dimensional measurement requirement. Commonly, the diamond indenter ground at 120 degrees for testing hardened steels and carbides. In another scenario the soft materials are usually tested by tungsten carbide balls the diameter varies from 1/16" up to 1/2". The combined indenter and applicable load made up the Rockwell scale. These combinations make up approximately thirty distinct measurements that are the widely detailed as the actual hardness number and marked by letters HR on the respective scale. In an existing literature the recorded hardness number for HRC is almost 63 under the Rockwell C scale. Moreover, the higher numbers are indicated the harder materials as tungsten carbide or hardened steel. Those material types have higher HRC values exceeding 70 HRC. Even though, the Rockwell test load could be implying for as standard deadweight systems or a closed loop load cell [47].

In addition, the micro and macro hardness testing processes are also referred to Knoop or Vickers testing. This means the test also carried out by pressing an indenter on a specified geometrical shape on the specimen surface. Unless otherwise, the Rockwell, the Vickers or Knoop testing applies in a single test force direction. The impression of the resultant or un-recovered area is measured with the help of a high-powered microscope in combination with Filar measuring eyepieces. In more contrast it is depending on automatically with image analyzing software. As far as, the Knoop diamond developed an elongated rhombic-based diamond shaped indent with a ration between long and short diagonals of about 7 to 1 [49].

Other way round the Vickers tests are mainly known as macro-indentation tests those are based on an extensive range of materials including case hardened along with the steel components. Moreover, the Vickers indents are also less sensitive with the surface conditions than the Knoop test. In above tests the measured area is employed in a formula includes applied force in order to determine a hardness value. The tabular format and automatic imaging either electronic measurements are the most common and convenient way to produce Knoop and Vickers hardness numbers [29-37].

1.6 Nuclear Materials

Nuclear engineering is the subdivision of engineering that related to the application of the nuclear fission and the nuclear fusion as well as other sub-atomic physics applications, built on the principles of nuclear physics. Generally, nuclear engineering compacts with the application of nuclear energy in a assortment of divisions such as, nuclear power plants, food fabrication, and naval propulsion systems [67].

The main goal in this section is to present the nuclear materials of nuclear reactors. The outcomes behind of thermophysical and characteristics of nuclear materials is necessary to design nuclear power plants. Generally, there are two basic brands of nuclear materials, which are used in nuclear power plant.

1.6 Materials having specific nuclear characteristics

These materials must satisfy very specific desires that originates mainly in atomic nuclei interactions. This class relates to the nuclear fuels as well as neutron absorbing materials, for example, alloys of_low neutron capture cross-sections. For these nuclear materials proper nuclear characteristics are a priority and the finest chemical state could be nominated in control rods such as, boron as a neutron absorber is good for using in water solution like boric acid or boron carbide – B_4C [68].

1.6.1 Standard engineering materials

These nuclear materials are not different from basic materials used in other engineering divisions. However, it must be noted nuclear engineering placed higher standards on material quality and reliability of materials used than in other fields of application. This class of materials includes alloys such as; structural steels, stainless steels, zirconium alloys, etc. Some specific alloys such as Zr have been developed for specific applications in water reactors. This Zr-alloy constitutes special properties suitable for nuclear material applications.

Vital materials applicable for building nuclear power plants can be allocated into the following categories [69]:

1.6.2 Nuclear Fuels

In general, these are any material that is burnable during nuclear fission to generate nuclear energy. Most nuclear power reactors utilized an enriched uranium as well as plutonium as a fuel. Most pressurized water reactors use the uranium dioxide, whiles some other reactor types use different fuel matrices such as MOX fuels etc

1.6.3 Neutron Moderators and Absorbers

Moderator materials are an important component in the reactor core that helps to control the behaviors of the neutrons present in the core. These includes the slowing down of these neutrons to sustain fission in order obtained thermal energies. The most commonly used moderators comprise of light water which forms approximately 75% of the world’s nuclear reactors. More also, solid graphite and heavy water forms 20% and 5% of moderators used respectively. Be and BeO have also been used rarely due to the costly nature of this material. Neutron absorbing materials in the core of the reactor are applied in the following three cases:

- As control rods are materials for installing safety systems in nuclear reactors core.
- As burnable absorbers distributed uniformly in fuel or positioned in certain sections of the reactor core.
- As a supplement to a moderator for the adjusting excess reactivity in the core.

1.6.4 Coolants

Water and steam form the main cooling medium in a reactor. These are common fluids applicable for heat exchange in both primary and secondary circuit. In the primary circuit, heat is being exchanged from the surfaces of the fuel rods through to the coolant. However, many other materials are used as a coolant depending on the type of reactor such as the gas cooled reactors uses carbon dioxide gas as coolant, heavy water as coolant in CANDU reactors, etc.

1.6.5 Structural Materials

Numerous materials are involved for designing nuclear reactor components depending on significant material properties required for a particular component. For instance, some materials ought to inherently possess lower neutron capture cross-section, principally in the reactor core in order not to absorbs the neutrons at a faster rate and so as to maintain a fission chain reaction. Also, there are several materials, which needs to have a higher capture cross-section for designing control rod materials. In this unit, the fundamental physical characteristics of some of these structural materials such as steels, and special nuclear grade alloys will be discussed.

1.6.6 Radiation Shielding

Blocks of lead, concrete or water are the most common radiation shielding materials used in the nuclear power plants. Also, there are several materials which can be applicable for radiation shielding purposes. However, this will depend on some principles of radiation protection to be decided on the material to use such as the type of radiation involved, its energy and several other factors. For instance, even depleted uranium can be engaged as a good shielding material from gamma radiation. On the other hand, shielding neutrons with depleted uranium is completely inappropriate.

1.7 Accident tolerant fuels (ATF)

These are series of new nuclear fuel concepts currently under research and development in order to enhance reactor fuel performance by increasing the efficiency of energy generation under normal, transient accident situations. These situations include loss-of-coolant and reactivity-initiated accidents. After Fukushima Daiichi nuclear accident in 2011, a conception on fuel behavior has been introduced in order to build a more robust fuel cladding systems for existing and future reactors. Zirconium alloy clad fuel plays a successfully role over the decades toward its properties of high burnup coupled with some outstanding properties and it continually undergoes development and numerous improvements for about 40 years. However, under severe accident circumstances, the extreme temperature of zirconium in steam interaction posed a major state of damage to the power plant. These advancements include:

- Specially intended additives to ordinary fuel pellets intended to increase various possessions and performance.
- Strong coatings applied to the outside of ordinary claddings intended to decrease corrosion, decrease the production of hydrogen can be formed under high temperature in accident cases conditions, and increase wear resistance.
- Development of totally new fuel designs using ceramic cladding as well as different fuel materials [69-73].

1.7.1 Types of Accident Tolerant Fuels

- Advanced Fuel Clad

Although present-day nuclear fuel designs are operating very well under ordinary plant conditions, remaining nuclear fuel designs considering as a challenged when put below beyond-design-basis severe-accident consequences. If such conditions happening, loss of coolant as long-term and high temperatures resulting of the fuel can chief to the degradation of fuel material cladding, which can early release of fission products.

Offered ATF concepts seek to decrease severe accident SA threats by increasing possible coping time, which necessary to operators for accident response, decreasing the extent and rate of heat as well as hydrogen generated from high-temperature HT of the steam oxidation, or decreasing severe accident consequences by increasing fission product FP retention. However, the desired characteristics for a practical ATF nuclear cladding material are pretty rigorous. Furthermore, to good material possessions at high temperature, the applicant material must be companionable with current fuel/core designs, also to provide economic operation with good neutronics. Furthermore, at high burnups, from an operational perception it must be higher reliable, corrosion resistance, as well as exhibit low embrittlement [74].

Due to the NEA report, there are five different classes of materials cladding designs were the purpose of the review:

- Coated and improved Zr-alloys,
- Advanced steels,
- Refractory metals,
- SiC and SiC/SiC-composite claddings
- non-fuel components such as SiC/SiC channel boxes or accident-tolerant control rods (ATCR) [72].

1.7.2 Advanced Fuel Pellets

Due to the NEA report, the fuel designs covered through the Task Force on Advanced Fuel Designs involve of three different concepts:

- Improved the UO2 fuel, regarding the enhanced UO2 fuel, this specific design was separated into two sub-concepts, for instance oxide-doped UO2, as well as high-thermal conductivity UO2, which was designed with addition of metallic or ceramic dopant.

- High-density fuel.

- Encapsulated fuel or TRISO-SiC-composite pellets.

1.7.3 SiC and SiC/SiC-composite claddings

However, SiC is exceedingly hard, synthetically formed crystalline compound of Si and C. A mohs hardness rating of SiC is about 9, approaching that of diamond. Moreover, hardness and crystals of silicon carbide have fracture appearances that make them more useful in grinding wheels. Also due to high thermal conductivity, as well as high-temperature strength, besides low thermal expansion, and chemical reaction resistance, makes SiC valuable in the production of high-temperature materials applications and other refractories [71].

In nuclear engineering applications, silicon carbide composite materials have been studied for using as a replacement aimed at zirconium alloy cladding in LWR light water reactors. Silicon carbide centered ceramics and their composites have superior high-temperature possessions, such as excellent irradiation resistance and inherent low activation, as well as other superior physical/chemical characteristics. Moreover, the composite involves of SiC fibers, which is located around a SiC inner layer then surrounded by a SiC outer layer. The Problems have been reported through the ability to join the parts of the SiC composite.

Silicon Carbide cladding is proposed to provide advanced safety margin improvements. SiC cladding reacts various orders of magnitude with water and steam slower than zirconium especially at critical temperatures (above 800°C), due to minimal generation of heat, as well as hydrogen in beyond-design-basis accident scenarios [69]. Moreover, SiC-composite claddings, as well as fuel components are expected to offer excellent passive safety features in design-basis accidents besides design extension environments severe accidents (SAs). Furthermore, the SiC/SiC composites are estimated to provide extra benefits over the Zr-alloys, for example a reduced neutron absorption cross-section permitting a smaller uranium enrichment. Also the combination of these striking features makes the SiC combinations one of the leading nominees for accident-tolerant LWR nuclear fuel cladding and core structures [66].On the other hand, SiC/SiC composite fuel clads have three main disadvantages:

- ❖ Fabrication of thin nuclear fuel clad needs further development. Hence, the SiC ceramics cannot be welded, a technology for end-plug connecting with gas tightness and sufficient strength should be as well developed.

- ❖ Tritium releases, due to a potential increase in tritium that release into the reactor coolant. Moreover, tritium is created as a fission product. SiC does not react with hydrogen to form stable hydrides similarly to a zirconium-based alloy, depending on higher permeability of tritium over the cladding to the reactor coolant. The select of using appropriate liner material could help mitigate this issue [74].

- SiC/SiC has significantly lower thermal conductivity than zirconium alloys. Therefore, its negatively impacts pellet centerline temperatures as well as the coping time.

One of possible SiC composite claddings has been developed by General Atomics and is known as SiGA™ silicon-carbide (SiC) composite, in which the SiC matrix material is reinforced with flexible SiC fiber in much the same way that steel rebar reinforces concrete. This creates an extremely hard and durable material that can withstand the harshest reactor conditions [69].

Chapter 2 – Description, Methods and Sample Preparations

2 Background study

The main advances of this particular chapter is to introduced with the main deposition/ coating fabrication methods. Due to the dispositioning, in this process, an atomized silicon carbide is used as deposited with the nuclear grade zirconium-alloy (Zr-1Nb). This Zr-1Nb does substrate towards to develop a suitable zirconium-based coatings for cladding material design. In more detailed study of this work the development of an Accident Tolerant Fuel (ATF) for VVER or PWR fuel cladding material within strengthening the existing and future LWR reactors fuel cladding system [75].

The diversity of the nuclear fuels those are composed by heavy fission actinide elements are capable of undergoing and maintaining the fission process. Such as, U-233, U-235 and P-239 are most widely usable isotopes of the nuclear fuels. The slow interaction of the neutrons collides with the unstable nucleus in the uranium fuel atoms. This means the reaction splits and creates two extra neutrons in addition to generating the incoming neurotic chain. The neurotic chain is continuously rectifying, hitting and splitting the numerous numbers of nuclei to generate. A mechanically controlled self-sustaining chain reaction in the nuclear reactor. As a result, the fuels used must be covered with a coating in distinctive characteristics. Zirconium-based alloys have served as the main cladding materials over the past decades to date in the design of nuclear fuel cladding materials [76].

SLS is competent of producing highly complex geometries. The SLS is an addictive manufacturing process in which the 3D printing could be used to fabricate and design material by joining and consistency under some computer manipulation [77]. This methodology is produced a high-heat and chemically resistant applications. Although the complexity of the SLS system, it is advantageous in managing time and cost of production. It is also applicable and possibility to design and build large stages for mega structural industrial fabrications. Under the consideration of the building print, to fill the hollow spaces with an unused powder simultaneously takes place. Subsequently making the SLS deposition self-supporting and maintaining a large degree of freedom in the design process [78]. The SLS technique has plenty of advances. At instance, the sintering SiC comes with pores of larger proportions. Nevertheless, the most recent works are proposed a novel 3D printing technique to improve the state of condensation. According to Terrani et al, 2019 [98] on "3D printing of high purity SiC" introduces a novel two steps as 3D-printing approach. A binder jet system is being used for printing.

In previous literature, numerous research works have shown that the authenticity of various coatings on zirconium substrates is efficiently in overcoming accelerated oxidation, resisting corrosion and lessening the susceptibility of grid-to-rod fretting failures [79]. The researchers are involved to improve coated cladding materials. An ATF coating technology ought to have one at least Cr, Al or Si in its elemental compositions [77] in order to enable the formation of these three conventional protective oxides (Cr_2O_3, Al_2O_3, and SiO_2) in protecting the basic material [60-63]. As a result, this work is used to deposit the commercial grade SiC on Zr-1Nb substrates.

2.1 Material Description and Preparation of the SiC coatings on Zr-1Nb

For the deposition of Zirconium (Zr-1%) fixed dimension (20 mm x 20 mm x 2 mm), is being used. The prior manufacturing process for all surfaces were polished to a level roughness of 0.3 micro-meter. The three-specimen dimensioned and working area as 400 mm^2 (20 mm × 20 mm). Each of sample has three separate coating with the difference in layer thicknesses of 200 µm. These parameters have been taken where the developing strategies from initial investigations. Table 2.1 and Figure 2.1 are summarized the typical characteristics and sintering cycles of SiC powder (grade: SIKA DENSITEC L, Norway) used in this research.

Table 2.1 – Properties of SiC powder (trade name: SIKA DENSITEC L) [12].

<table>
<tr><td colspan="7">Compositions</td></tr>
<tr><td>SiC type</td><td>Al_2O_3</td><td>Y_2O_3</td><td>Binder</td><td colspan="2">Moisture content</td><td>SiC 4H & 6H</td></tr>
<tr><td>Sintex 13C</td><td>5.5 %</td><td>3.5%</td><td>6 %</td><td colspan="2">1 %</td><td>~84%</td></tr>
<tr><td colspan="7">Typical Physical Properties</td></tr>
<tr><td>Average grain size</td><td>Bulk density</td><td>Hall Flow</td><td>Appearance</td><td>Density</td><td>Elastic Modulus</td><td>Fracture toughness, K_{IC}</td></tr>
<tr><td>100 µm</td><td>0.86 g/cm^3</td><td>22.5s / 50g at 20 °C</td><td>Light color</td><td>3.21 g/cm^3</td><td>24 GPa</td><td>4.5 MPa $m^{1/2}$</td></tr>
</table>

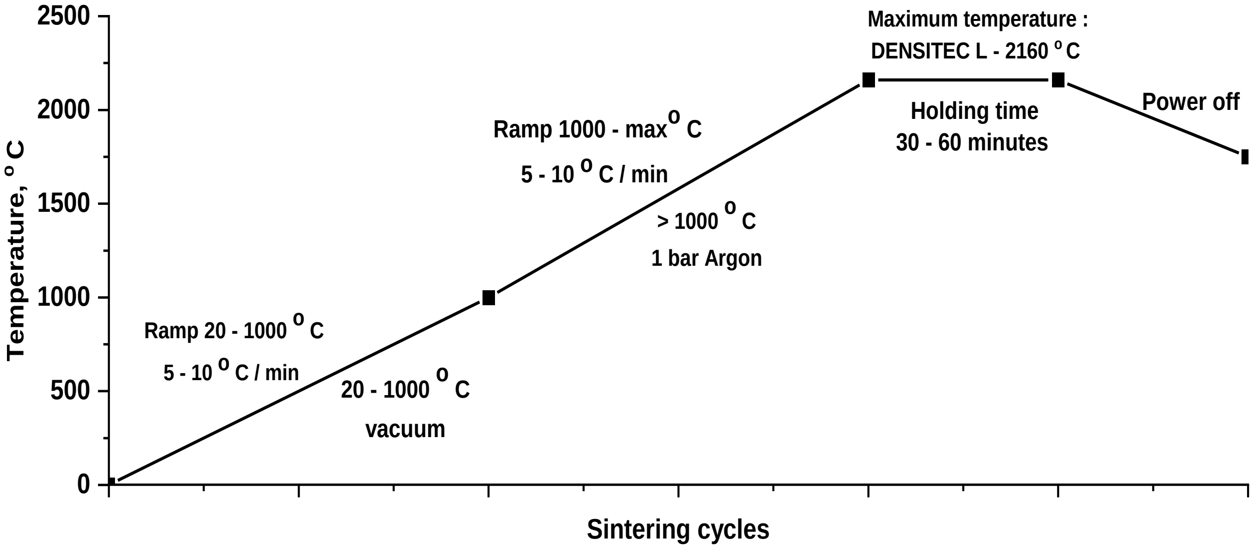


Figure 2.1 – Scheme of a typical sintering cycles of the SiC powder used [64].

2.1.1 The Experimental Setups of Fabrication process

In SLS system a Ytterbium green laser is being used with an output wavelength of 1070nm and a maximum power of 500W. In a manufacturing context, a laser power around 125W was used. Within a natural air, a substrate is considered to work at the time by carefully placing it in the chamber filled. In order to achieve sintering, the SiC powder then sintered with the heat generated by the laser on increasing the local layer temperature just below the melting point. The laser heats the SiC particles in specified directions until it is completely sintered through successive deposition. The lowering of the build platform whilst raising the delivery platform determined by the step size completes each layer thickness deposited. A layer thickness of 200 µm is established per the labels a, b, and c, respectively through repetitive deposition. Furthermore, a 3D-CAD extension file in stereolithographic “stl” format dictates the sintering path as programmed. The printed object from the powder bed is completely withdrawn from the chamber which is followed by a post processing technique of dusting. The Figure 2.2 and Table 2.2 are depicted a brief scheme of SLS setup, and the parameters followed in the fabrication process [61-66].

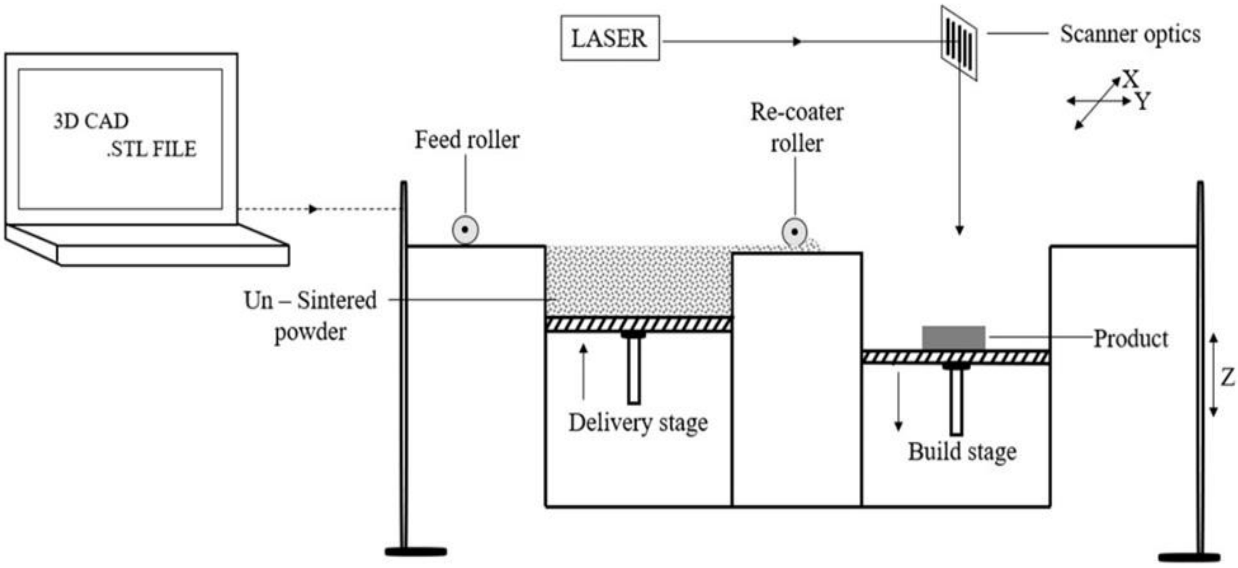


Figure 2.2 – Schematic view of the SLS setup.

Table 2.2 – Parameters followed in the SLS fabrication.

Samples	Laser power (W)	Scanning time (µs)	Laser speed (mm/s)	Coating thickness (µm)	SLS Filled Chamber
Sample 1	125	500	25	200	O
Sample 2	125	500	25	200	Ar

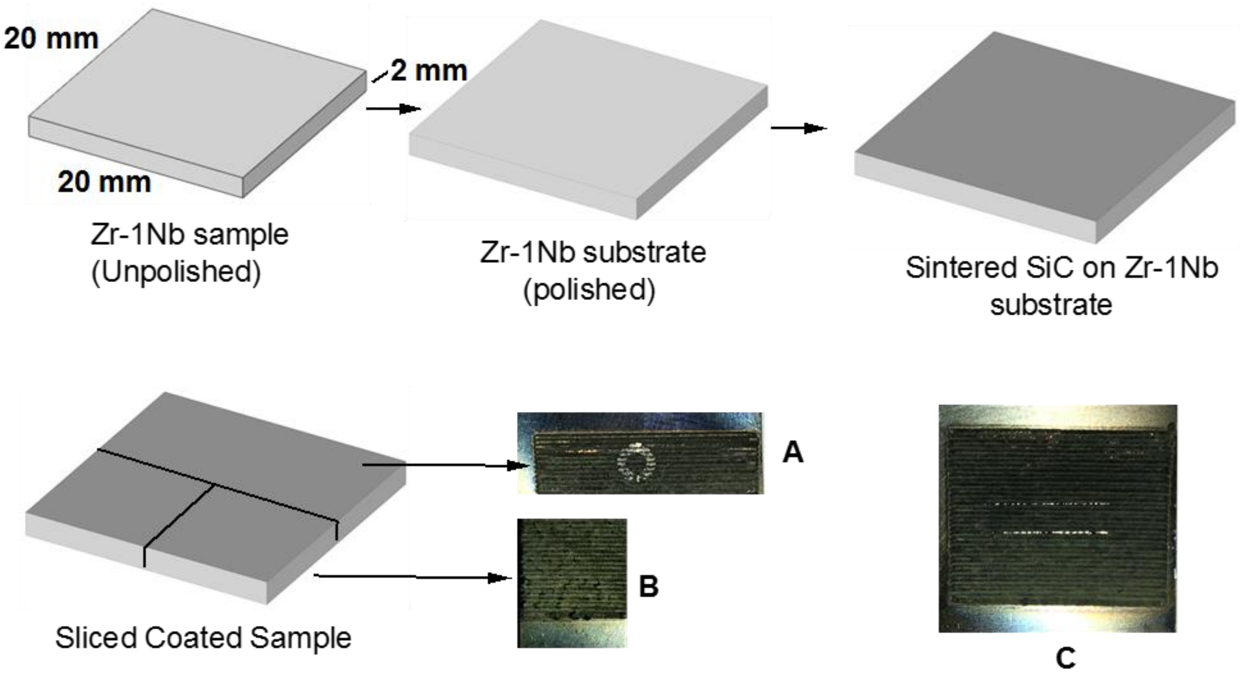


Figure 2.3 – Schematic process undergone by samples in the coating of SiC on Zr-1Nb alloy. **A, B** and **C** represents the actual sliced samples for tribology, and scratched adhesion tests and micro-indentation respectively.

The table 2.3 stipulates some important properties of nuclear grade zirconium alloy previous used in the nuclear industry and SiC as a potential material for zirconium alloy surface modification for nuclear fuel cladding studies.

Table 2.3 – Mechanical and Thermal Properties [45-48].

Mechanical Properties				
Parameters	**SiC**	**Zry-4**	**E110**	SI / Metrics
Density	3.0 - 3.2	6.56	6.63	g/cm^3
Elastic Modulus	410	99.3	93	GPa
Yield strength	175 – 705	381	350	MPa
Poisson’s ratio	0.35 – 0.37	0.37	0.38	
Shear Modulus	32 – 51	36.2	-	GPa
Tensile strength	240 – 1625	514	450	MPa

Melting point	2730°C	1850	1852	°C
	Thermal Properties			
Thermal conductivity	3.8 – 20.7	21.5	55.4-75.5	W/m. K
Specific heat	670 - 1180	285	456	J/kg-K
Coefficient of Thermal expansion	3	6	5.5 -5.8	µm / m^{o}K
Thermal Neutron Cross-section	0.09	0.22		barns/atom

2.2 Brief Overview of XRD Phase Composition

The further investigation of X-rays by Wilhelm Conrad Roentgen in 1895 allowed an important evolution in all scientific disciplines, considering the development of new medical as well as the technical applications possibilities. Nowadays, these methods have been further developed to become very powerful tools in the fields of materials science and engineering [81].

The experimental methods are based on X-rays that are used in materialistic science could be classified into subcategories (Spieß et al., 2009). Among of the three categories X-ray fluorescence spectroscopy is widely used for qualitative and quantitative chemical analysis, in particular, in electron microscopes. Furthermore, the X-ray radiography the technique of an imaging process which is based on the intensity of passing through by using the films or detectors which follows internal structure and the local variation of the absorption. The XRD methods are based on the ability of crystals to diffract X-rays in a characteristic manner allowing a precise study of the structure of crystalline phases [82].

In more contrast the recorded diffraction patterns contain additive contributions of several micro- and macro-structural features of a sample. On above the peak points of its position, lattice parameters, space group, chemical composition, macros-tresses, or qualitative phase analysis can be investigated. The fundamental of the peak intensity, information about crystal structure (atomic positions, temperature factor, or occupancy) as well as texture and quantitative phase analyses can be obtained [83].

2.2.1 System Characterization of the XRD

In this experiment the phase composition of the coating surface was investigated by an X-ray diffraction in single phase to twice as θ - 2θ. This type of the system is equipped with OneSight wide range 1280 high-speed detector system. The XRD system was operated with Cu radiation at 40 kV and 30 mA. The coated samples were scanned in a step scan mode with 250 channels at a scan rate of 10 deg/min with a start angle of 10^0 to an end angle of 90^0 at a dwell time of approximately 11 minutes. The raw diffraction data was analyzed with the help of the Sleve+ program. Search-Match and PowderCell24 together with PDF-4+ database was used in analyzing the diffraction spectra and to identify the multi-phase of the elemental compositions [70-74].

Figure 2.4 – XRD 7000 diffractometer maxima (Shimadzu, Kyoto, Japan).

2.3 Micro-IndentationTests

The micro-indentation test for this research was performed with the test platform of KB Hardwin XL indentation set-up as shown in the Figure 2.5 The experimental set-up integrates a number of variety of technologies. The experimental tool is allowable of applying and measurement loads ranges 0.1 and 100 N. The calibration needs to be conducted before performing using the system for the test. The load and indentation depth transducer are calibrated by using friction signal processor, load magnification potentiometer and zero potentiometer. While another vital component of the indentation test is indenter, which can be classified as pyramid indenter (Vickers indenter). The Vickers indenter, a four-sided pyramid, is a standard indenter used for micro-hardness testing. For SiC coated zirconium, the Vickers indenter was utilized in this study [80-85].

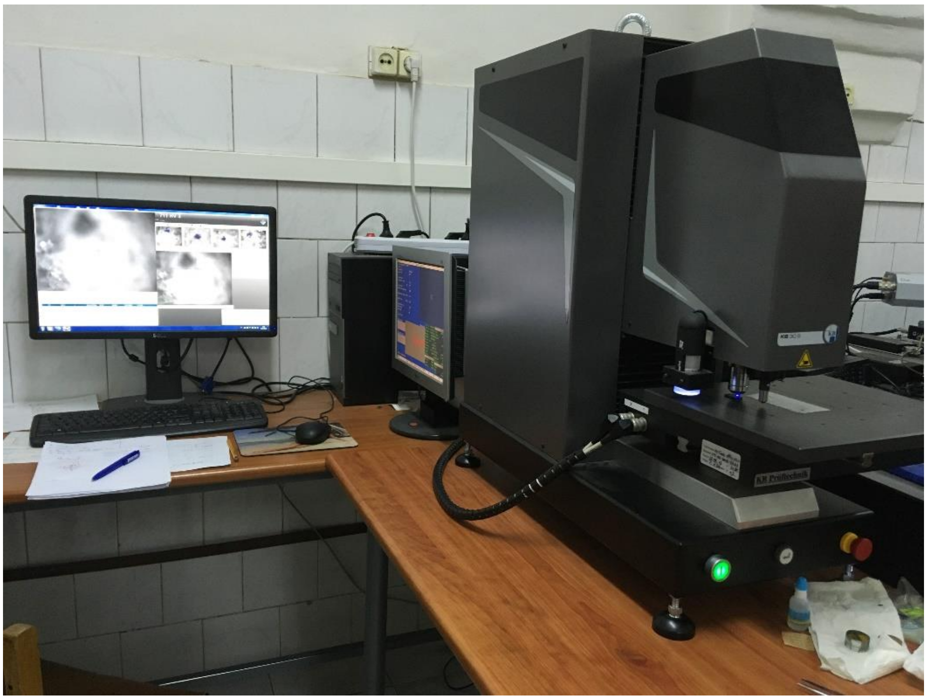
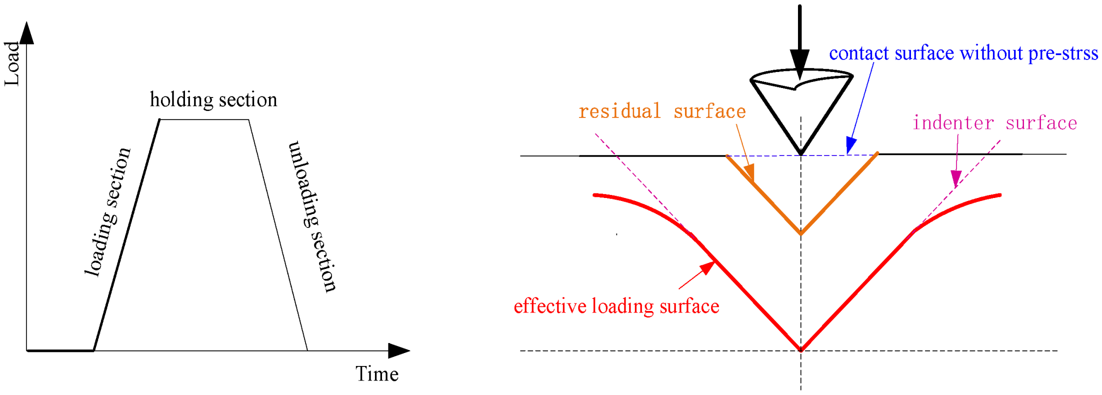


Figure 2.5 – Micro-indentation setup.

2.3.2. Experimental procedure

The simplest procedure for the preparation of an indentation experimental work is depicted by Figure 2.6 Initially, the indenter tip should be in contact with the specimen upper surface under any load. Furthermore, the calibration is held effectively in order to minimize the systematic errors in the experimental data. At the final stage of indentation preparation in the beginning, the surface of indenter tip is under pressured of the standardized surface at a fix loading rate. On achieving the maximum load, the sample is maintained to endure the time-dependent deformation. Finally, the deformation of the indenter tip slightly changed and under consideration of the loaded stress. During the experimental process, the load and depth data of the indenter were recorded by the sensor [86].



(**a**) Indentation loading function (**b**) Typical indentation response

Figure 2.6 – Schematic diagram of typical indentation loading function.

2.3.3 Environmental Control

Aforementioned, the significant influence factor, the experimental environment has to be taken into an account. The material surface and the tools could undergo expansion under specific temperature during indentation experiment and therefore required to be controlled. The process could be influenced and distort the accuracy of the measurement during the experimental process. The experimental setup was established at a temperature range of 25 ± 1 °C with relative humidity less than 50%. for the micro-indentation test of test specimen [83].

2.4 Scratch Adhesion Test Investigation

Hard coatings are able to improve the lifetime of industrial components because of their excellent wear and corrosion resistances [1, 2]. Due to high strength, high hardness and high melting points of SiC [3], the deposition of Silicon carbide (SiC) dispersed on a substrate from the surface to a depth of several tens of microns, forming a coating that will improve the adhesion and tribological properties of the material surface [4,5]. The scratch experimental testing is an also essential method for investigating and adhesion because it is one of the few tests several researchers used in their investigation [15–18] in order to study the adhesion and failure behaviors of coatings on substrate materials using a developed scratch tester. This type of the methodology can linearly ramp up the load during scratching. For the cracking, spallation on the scratch track border, or coating detachment in the center of the crack [15] occurs at a critical load (Lc), which can be determined by both acoustic emission (AE) and failure image under scanning electron microscopy (SEM).

Further, the investigation of adhesion and deformation was carried out using the Rockwell cone, apex angle 120 degrees with 200 microns diameter single scratch tester. The expected load is confirmed by the scratch tracks and acoustic emission signals. Acoustic emission signals were measured with a 200 μm tip radius cone-shaped diamond indenter under constants loads of 50N, and 100N along scratch length of 10 mm [17].

2.5 Tribological Investigation

Zirconium based alloys are distinctive structural materials used in nuclear reactors and chemical corrosion resistant equipment. These mechanical properties, corrosion resistance, outstanding nuclear properties, are discussed in [83]. The development of generation four reactors types with higher burnups, higher neutron flux and higher temperature operating conditions, Zr-alloys ought to be modified to cope under normal and worse conditions [34]. Therefore, there is the need to improve the physio-mechanical properties of the material as well as corrosion and wear resistances in metals more importantly in Zr-based alloys.

The normal load applied was approximately 5 N at a sliding speed of 2 cm/s and sliding time of 10 min. The diameter of the tribo-tester ball was 0.98 mm with dimension of 3.0 mm and acquisition rate of 2.0 Hz. The room temperature and humidity were kept at 25 °C and 50% respectively. Sliding cycles of 30,000 laps was engaged. The coefficient of friction (COF) and the number of sliding cycles were recorded automatically through a data acquisition system [79-83].

Chapter 3.0 – Experimental Results and Discussions

3.1 Results and Discussions on the Phase compositions

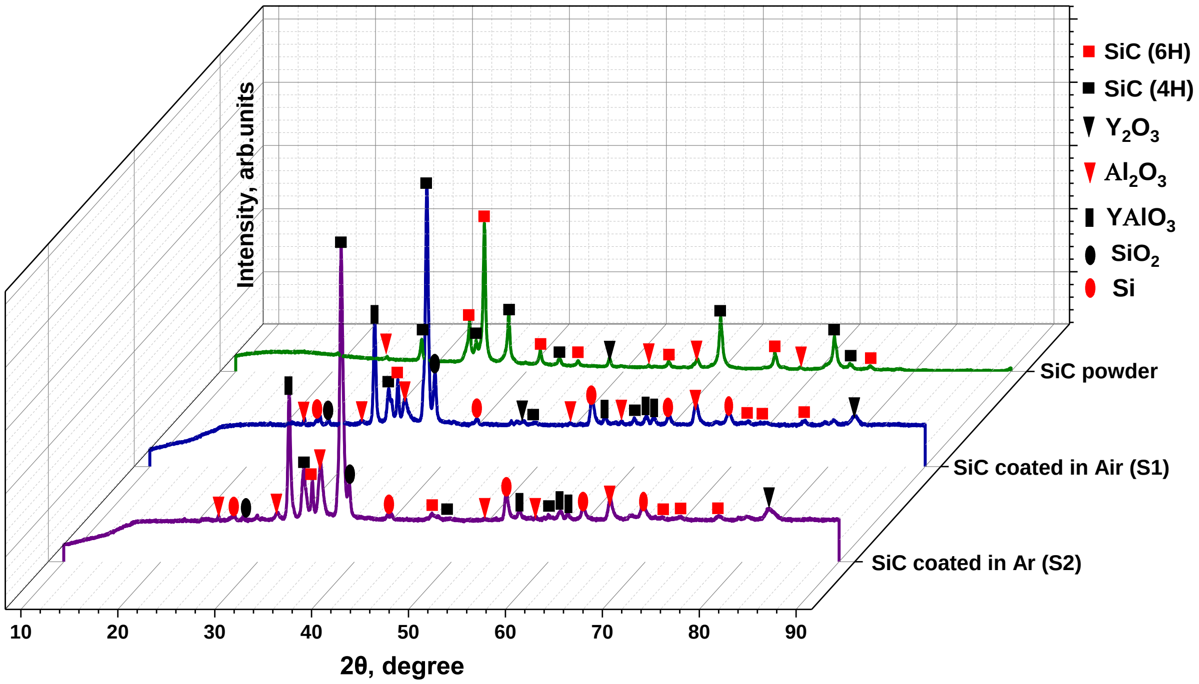


Figure 3.1 – XRD phase composition of samples.

Figure 3.1 shows the significant phase compositions which were observed on the samples surface to sub-surfaces. According to the Figure 3.1, it is clearly seen that four main phases including SiC(6H), SiC(4H), Y2O3 and Al2O3 were seen on all samples which forms the main phases of the SiC powder from the manufacturer as stated in the Table 2.1. After Selective Laser Sintering of SiC powder on the Zr-1Nb alloy, oxides phases including SiO_2 and $YAlO_3$ were formed as shown on the Figure 3.1.

3.2 Results and Discussions on the Indentation test

Figure 3.2 depicted depth of penetration in Vickers indenter during an individual sample as considered the function of the load applied. The equation 3.1 describes the relationship between the function of depth d and average diagonal distance h. As, shown by Figure 3.2 all samples penetration depth increases as the load increases on the indenter surface. Moreover, there is a vast increase in the depth formed in bare E110 alloy compared to those of the coatings. For instance, applying 100 N indenter load, the depth of indenter penetration and hardness for bare E110 alloy was about 56 microns and 238HV respectively while after coating, depth of indenter penetration as well as the hardness measured was about 22 microns and 1615HV correspondingly resulting to about 6.8 times the hardness and less than half the depth created in the bare

E110 alloy. The sample of the air atmosphere during SiC coating was recorded the least indentation depth and formation of the process of sintering followed by Ar atmosphere coated samples.

$$h = \frac{d/2}{tan68} \tag{3.1}$$

Table 3.1 – Vickers Hardness, average diagonal and depth of indenter penetration.

E110	h /µm	SiC/E110 (Air)	d/ µm	h /µm	SiC/E110 (Ar)	d/ µm	h /µm
222HV10	18.5	1209HV10	39,2	7.92	693HV10	51,7	10.44
212HV20	26.7	1800HV20	45,4	9.17	1673HV20	47,1	9.51
207HV30	33.2	1574HV30	59,5	12.02	1104HV30	71,0	14.34
218HV50	41.6	1549HV50	77,4	15.64	843HV50	104,8	21.17
238HV100	56.3	1615HV100	107,2	21.66	922HV100	141,8	28.65

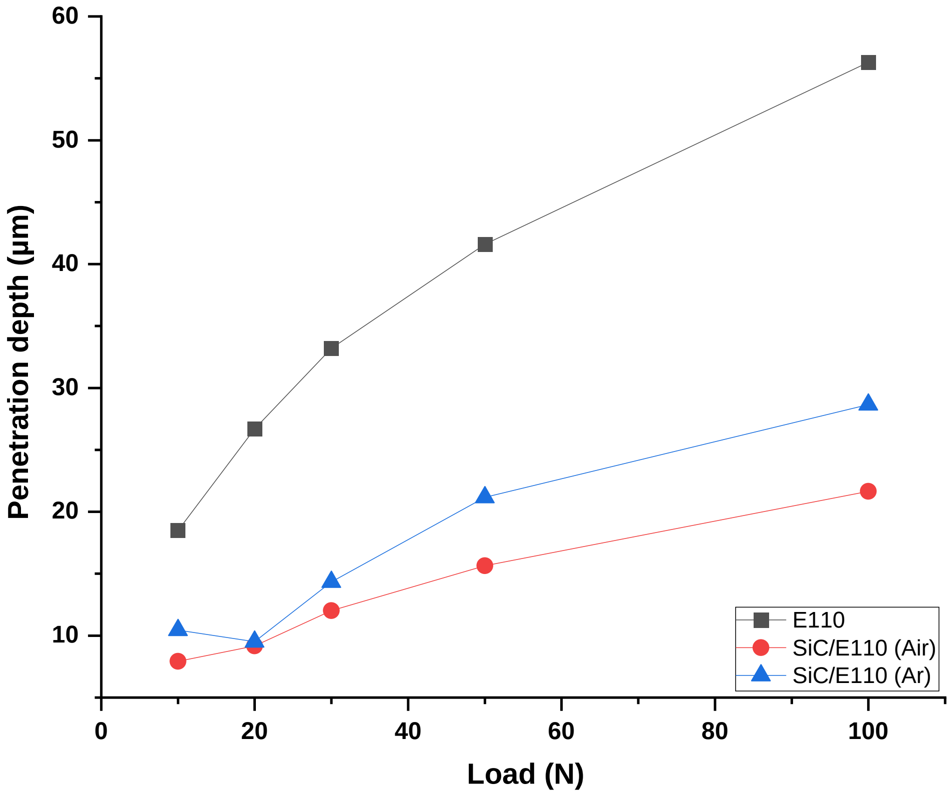


Figure 3.2 – Graph of indenter penetration depth against Load.

Table 3.2 – Indenter Load against Indentation Elastic Modulus of samples.

Load (N)	**E110(HV)**	**Elastic modulus (GPa)**	**SiC/E110(HV) (Air)**	**Elastic modulus (GPa)**	**SiC/E110 (HV) (Ar)**	**Elastic modulus (GPa)**
10	222	2.177	1209	11.86	693	6.796
20	212	2.079	1800	17.65	1673	16.41
30	207	2.030	1574	15.44	1104	10.83
50	218	2.138	1549	15.19	843	8.267
100	238	2.334	1615	15.84	922	9.042

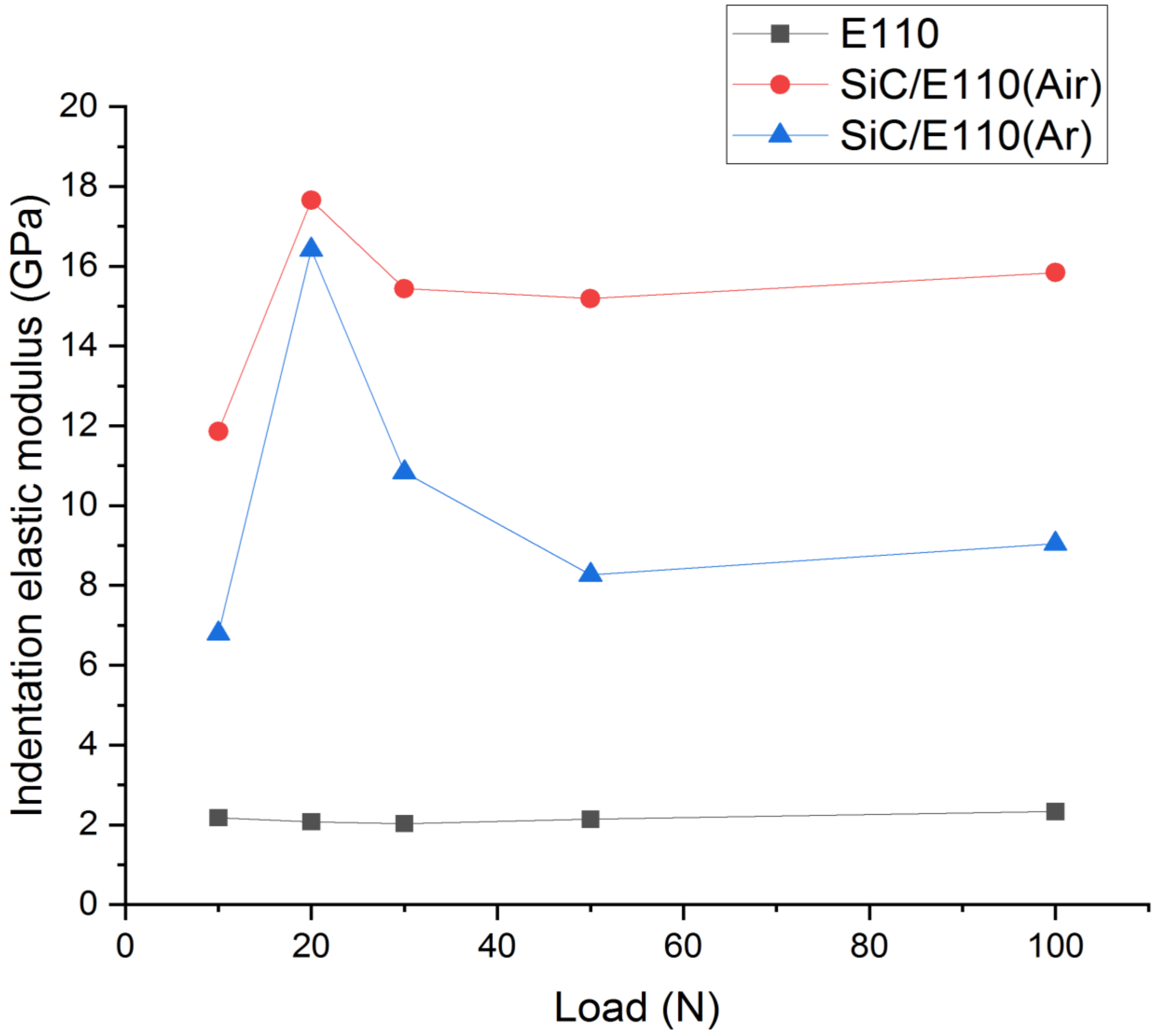


Figure 3.3 – Graph of Indenter Load against Indentation Elastic Modulus of samples.

The SiC coatings proves to resists the indenter from forming deeper depths into the specimen as a result of the presence of oxides. These includes SiO2 and YAlO3 which formed on the samples surfaces. Figure 3.3 shows an indentation elastic modulus as a function of the indenters' load. As depicted in the Figure 3.3, it can be clearly seen that bare E110 alloy indentation elastic modulus ranges uniformly between 222HV to 238HV. SiC coated E110 alloy indentation elastic moduli range between 1209HV to 1615HV, hence yielding extremely higher hardness and indentation elastic modulus as shown in the Figure 3.3 but slightly varies from chosen area engaged in the indentation. Also, indentation performed in the sintering tracks or in between track created during laser sintering can cause huge variation in the hardness obtained at such areas. For instance, indentation performed on the sintered tracks will yield greater hardness as well as indentation elastic modulus than indentation tests performed along the track gaps which was later filled with the SiC powder. Therefore, sintering tracks needed to be closer to each other in order to minimize porous gaps on the surfaces of the coating. These gaps will also require a post finishing technique such as infiltrating the pores with pure Si and Cr using chemical vapor infiltration technique, which can be accompanied by polishing so as to closely eliminate pores on the samples surfaces.

3.3 Results and Discussions on Scratched Resistance of Sintered SiC

Nano to micro scratch investigations were not applicable to the coating as a result to the higher level of adhesiveness exhibited by the thick coatings, hence macro-scratch test was performed with constant loads of 50 N and 100 N. Figure 3.4 shows the scratch tracks and its related features. Scanning electron microscopy observations along the coating paths reveal fewer degradation in spite of the higher magnitude of load applied by the diamond stylus during the test. Scratch widths formed by 50N and 100N generated approximately 110 and 140 microns for both air and Ar atmosphere-coating conditions.

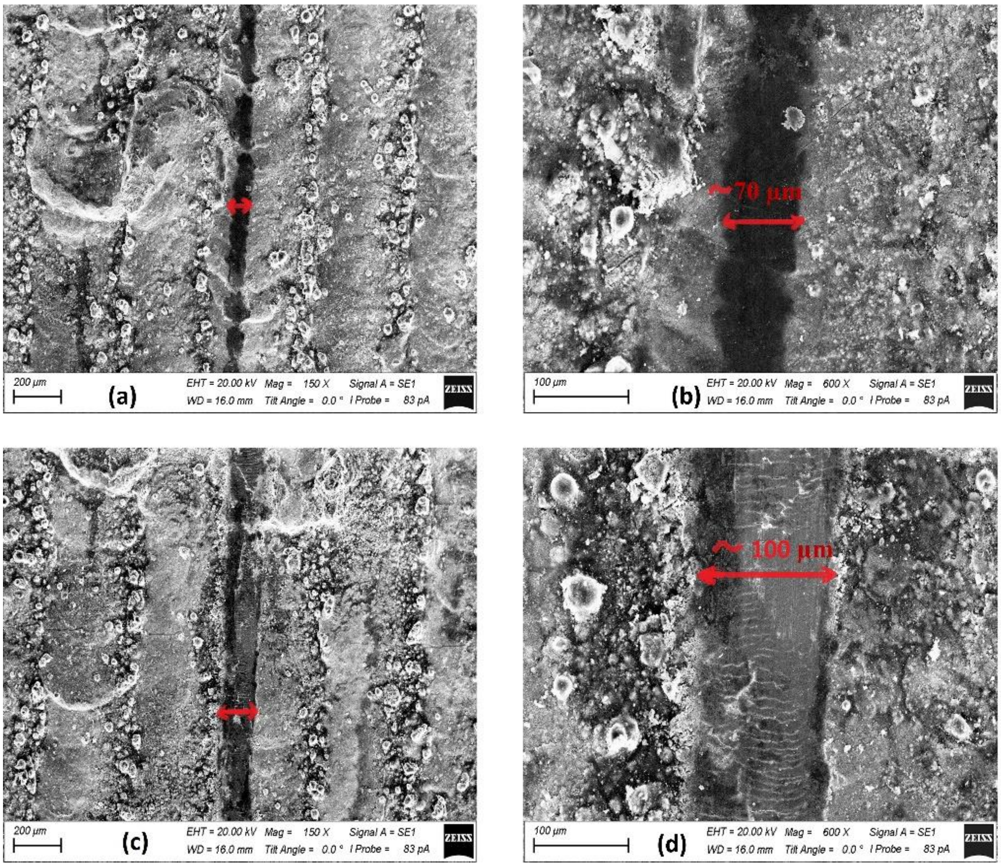


Figure 3.4 – A typical micrograph of the scratch tracks through the Air coating specimen.

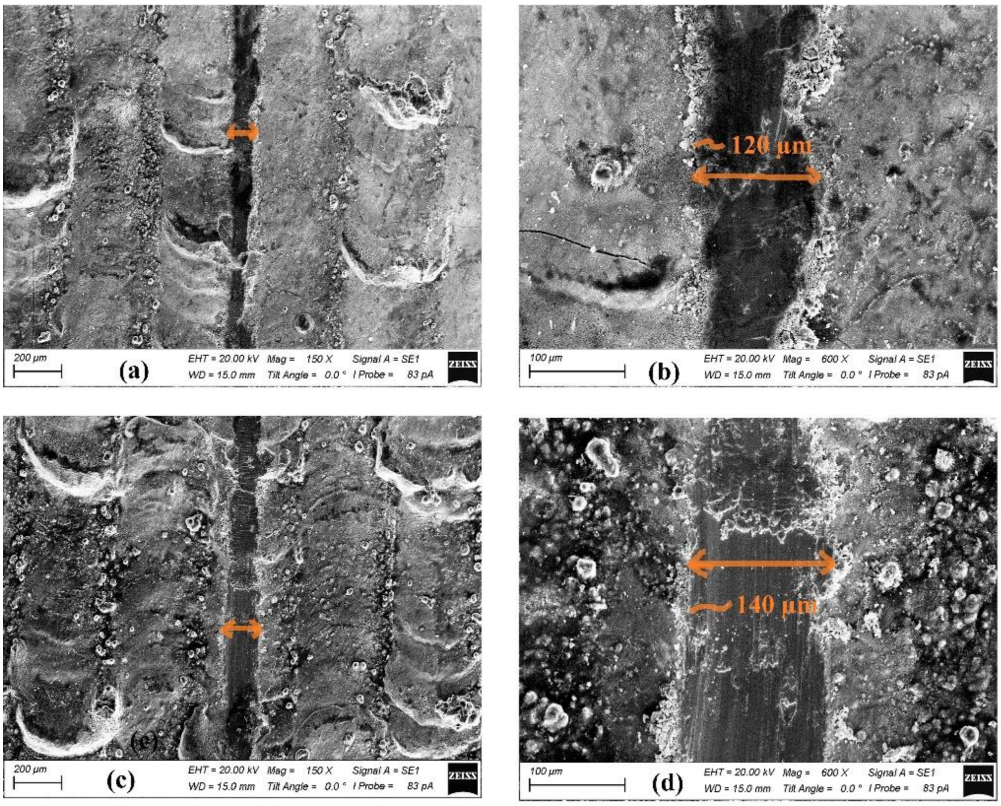


Figure 3.5 – A typical micrograph of the scratch tracks through the Ar coating specimen.

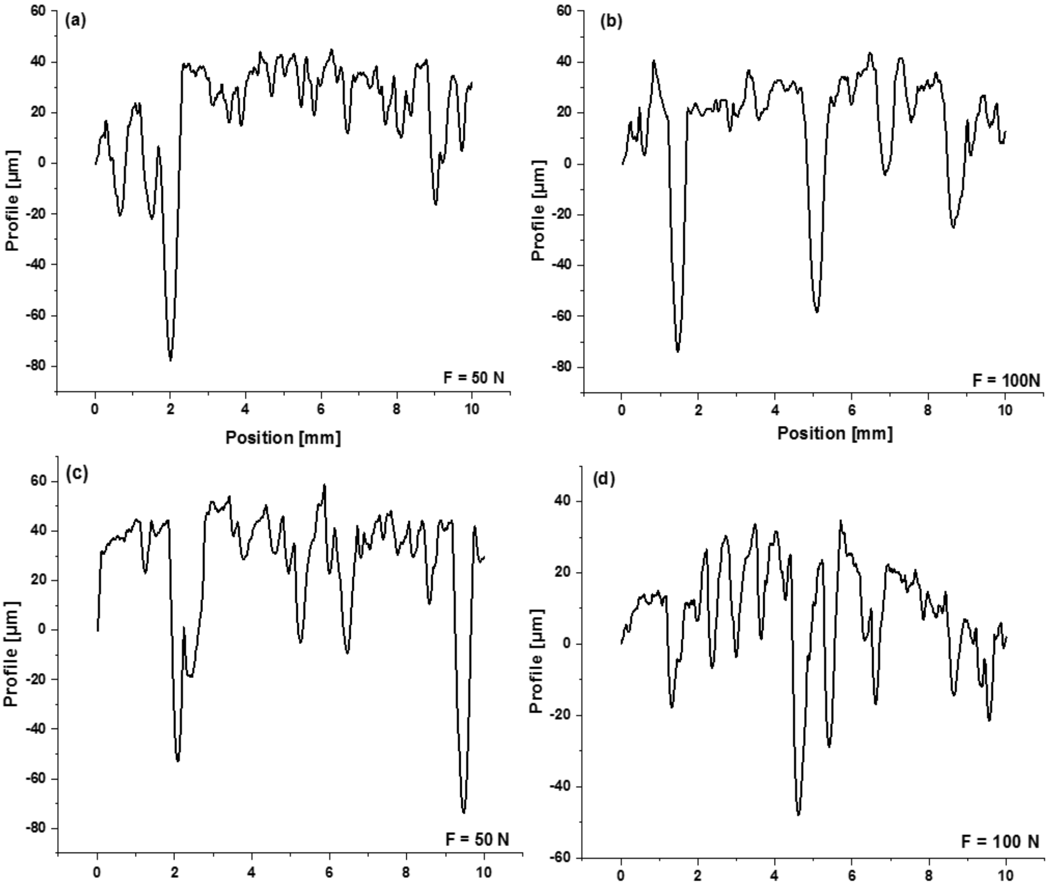


Figure 3.6 – Scratch profile and corresponding length along the scratch path.

According to Figure 3.4, scratch width created by stylus in the coating perform in air resulted to approximately 70 µm and 100 µm for the loads 50 N and 100 N respectively. Meanwhile, scratch width created in coating performed in Ar atmosphere presented approximately 120 µm and 140 µm for the loads of 50 N and 100 N correspondingly as depicted in Figure 3.5. In comparison, width created along the scratch paths in samples fabricated in Air were less of about 40 to 50 µm when compared to that samples coated in Ar environment. Figure 3.6 presented the scratch profiles along the scratch length. According to these profiles, SiC coated in Air atmosphere shows the least depth created by the scratch stylus of an average of 20 µm to 28 µm. While, SiC coated in Ar atmosphere provides an average depth of about 20 µm to about 40 µm.

3.4. Results and Discussions on the Tribological Test

The wear behaviors for all of these samples were assessed by observing and measuring their wear track profiles. The worn surface morphology is related to the wear mechanism. Figure 3.7 shows a typical SEM micrograph of the worn surface morphology for both samples. Figure 3.7 a and Figure 3.7 d present a complete wear track after tribology tests for sample coated in air and Ar respectively. Critical observations show less tribological wear on sample sintered in air atmosphere compared to that of samples sintered in Ar atmosphere. However, the major sintered tracks remain intact after the tribology test. This observation will guide future work on eliminating track gaps in strengthening the coating since these tracks were not worn out during tribology tests. In addition, observations on Figure 3.8 presents the worn parts of the samples from sides, top and bottom from optical microscopy point of view. It is known that the wear resistance of the coated substrate usually relates to the microstructure [80]. Therefore, samples coated in air atmosphere possessed an extra advantage of resisting wear than sample coated in Ar which might be attributed to the fact that excess oxides such SiO2 easily formed during the sintering process in an air-filled chamber.

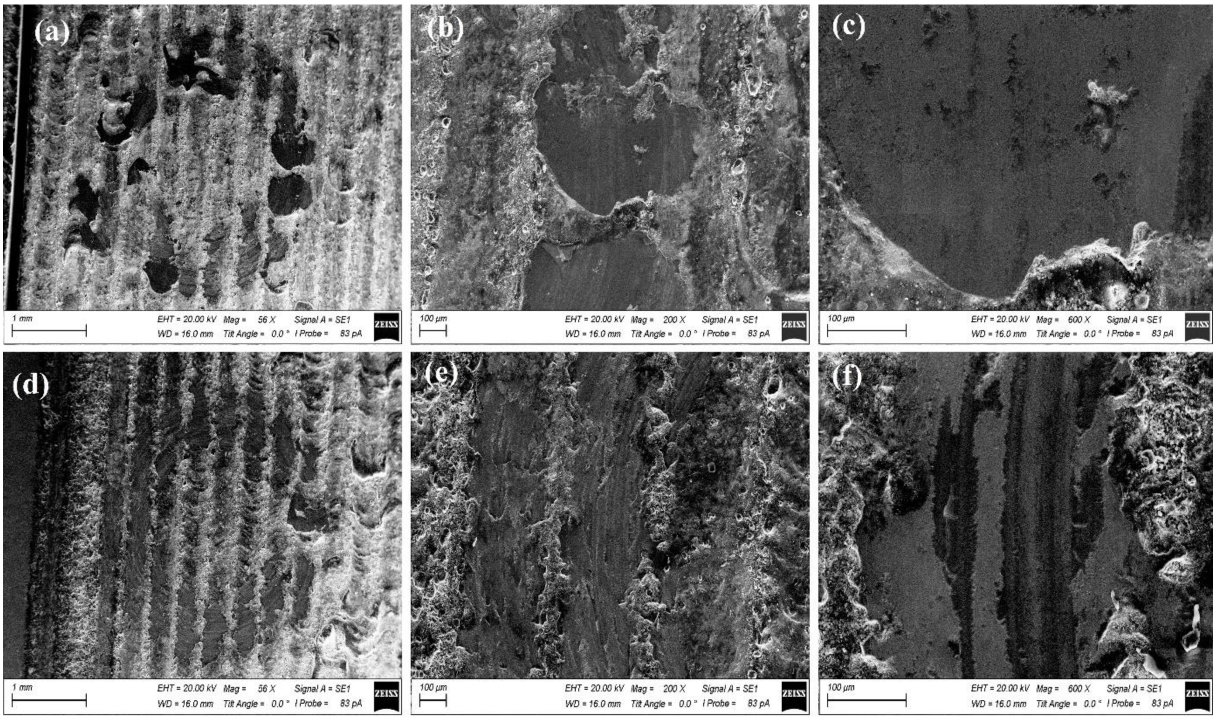


Figure 3.7 – SEM Micrograph of tribological wear on samples. a,b,c for sample 1(coating in Air atmosphere) and d,e,f for sample 2 (coating in Ar atmosphere).

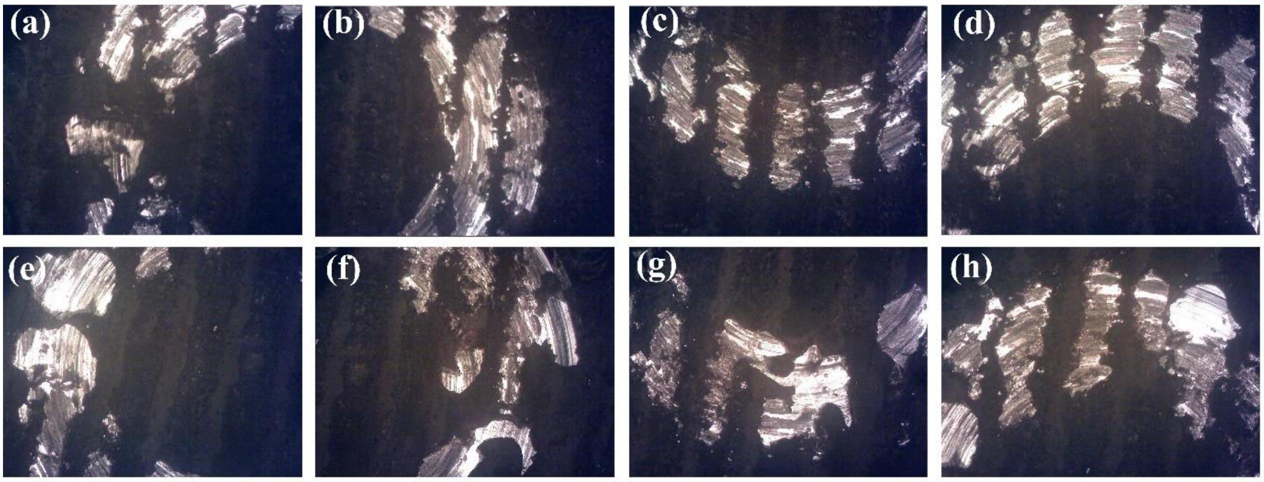


Figure 3.8 – Optical Micrograph of tribological wear on samples. a,b,c and d for sample 1 and e,f,g,and h for sample 2.

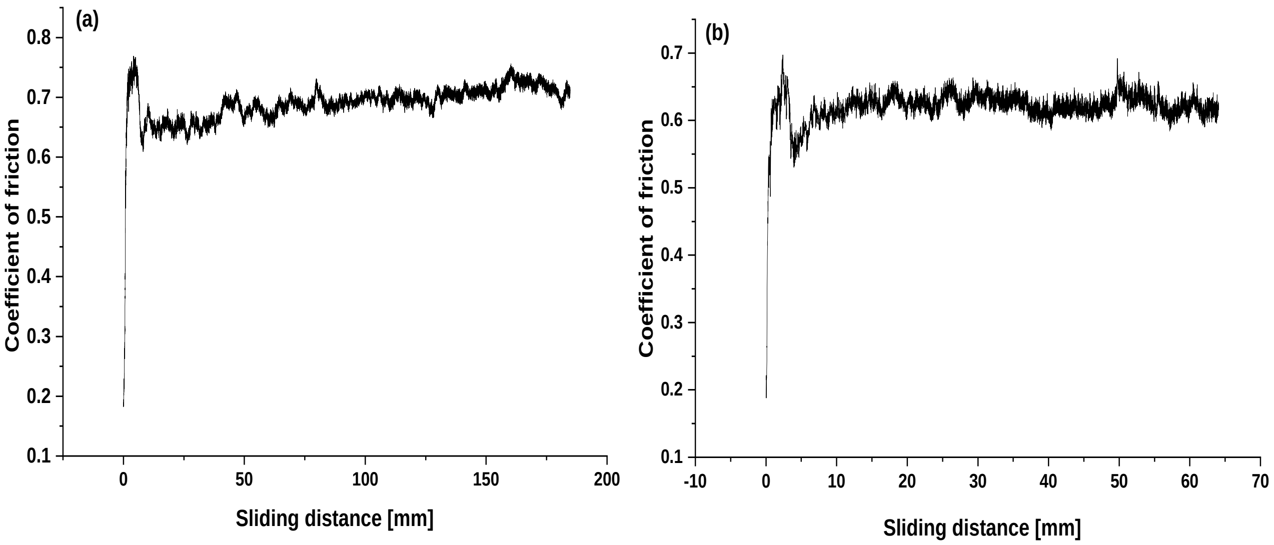


Figure 3.9 – Coefficient of friction as a function of sliding distance during tribology investigation, **a** and **b** represents Sample 1 and sample 2 respectively.

Figure 3.9 shows the frictional coefficient profiles against sliding distance. Sample 1 which was sintered in air atmosphere recorded slightly higher friction coefficient of 0.690 ±0.038 with a minimum and maximum friction coefficient of 0.182 and 0.769 respectively. However, sample 2 which was sintered in Ar atmosphere recorded 0.646 ± 0.043 with minimum and maximum friction coefficient being 0.183 and 0.707 respectively.

Conclusion

SiC micro-composites were deposited on E110 alloy substrates in air and *Ar* atmosphere using selective laser sintering and investigated under mechanical tests such as micro-indentation, scratch adhesion, tribology and phase composition. Micro Indentation results proves SiC coated Zr-alloy having greater hardness as well as higher indentation elastic moduli compared to that of uncoated Zr-alloy which manifested in the lower depth penetration of the coating. Scratch adhesion investigation endorses SiC coated in air atmosphere to be more robust against scratch width and depth creation in the coatings than those fabricated in Ar atmosphere with less of about 40 to 50 μm in width and less of few microns in depth when compared to samples coated in Ar environment. SEM results and observations proves SiC coated in air filled chamber possessing a slightly extra resistance of about 6.4% against tribological wear and degradation with slightly higher coefficient of friction of 0.690 ±0.038 when compared with SiC coated in the Ar filled chamber with coefficient of friction of 0.646 ± 0.043. XRD phase qualitative analysis reveals the formation of essential oxides including SiO2, YAlO3 for protecting the coating layer from atmospheric contaminants in addition to the primary phases observed in the atomized SiC powder such as Y2O3 and Al2O3. In general, the mechanical endurance to wear, scratch and indented depth results of the SiC coatings provides superior mechanical characteristics over bare Zr-alloy. These results fundamentally provide some information regarding the enhancement of the robustness of future LWR cladding component materials which deserves the necessary attention and can be recommended for further research for designing fuel cladding systems of improved safety properties for future nuclear industries.

Chapter 4. Financial management, resource efficiency and resource saving

The purpose of this part to discusses the issues of competitiveness, resource efficiency and resource saving, as well as financial costs regarding the object of study of master’s thesis. Competitiveness analysis is carried out for this purpose. SWOT analysis helps to identify strengths, weaknesses, opportunities and threats associated with the project, and give an idea of working with them in each particular case. For the development of the project requires funds that go to the salaries of project participants and the necessary equipment, a complete list is given in the relevant section. The calculation of the resource efficiency indicator helps to make a final assessment of the technical decision on individual criteria and in general.

The benefit of the coating silicon carbide powder on zirconium alloy substrate which is used in water reactor cladding, such as Light water reactor (LWR) in this research will save a lot of money as a safety technique, and it has high thermal and mechanical efficiency that make it is required in global trade market.

4.1 Competitiveness analysis of technical solutions

In order to find sources of financing for the project, it is necessary, first, to determine the commercial value of the work. Analysis of competitive technical solutions in terms of resource efficiency and resource saving allows to evaluate the comparative effectiveness of scientific development. This analysis is advisable to carry out using an evaluation card.

First of all, it is necessary to analyze possible technical solutions and choose the best one based on the considered technical and economic criteria.

Evaluation map analysis presented in Table 4.1. The position of your research and competitors is evaluated for each indicator by you on a five-point scale, where 1 is the weakest position and 5 is the strongest. The weights of indicators determined by you in the amount should be 1. Analysis of competitive technical solutions is determined by the formula:

$$C = \sum W_i \cdot P_i, \tag{4.1}$$

C - the competitiveness of research or a competitor;

Wi– criterion weight;

Pi – point of i-th criteria.

Zr-1%Nb and Zr-2.5%Nb are currently the main competitor to Silicon Carbide (SiC) in core cladding in water reactor because they were the first alloys used as a cladding to old reactors. However, there are strong recommendations for actively searching about other new materials which have higher thermal mechanical properties such as SiC due to serious accidents that were happened because of Zircalloy like what happened in the disasters such as: Chernobyl 1986 and Fukushima 2011.

Table 4.1 – Evaluation card for comparison of competitive technical solutions.

Evaluation criteria	**Criterion weight**	**Points**			**Competitiveness** Taking into account weight		
Example		P_f	P_{i1}	P_{i2}	C_f	C_{i1}	C_{i2}
1	2	3	4	5	6	7	8
Technical criteria for evaluating resource efficiency							
1. Energy efficiency	0.1	5	5	3	0.5	0.5	0.3
2. Reliability	0.2	5	3	5	1	0.6	1
3. Safety	0.1	4	5	4	0.4	0.5	0.4
4. Functional capacity	0.3	5	4	4	1.5	1.2	1.2
Economic criteria for performance evaluation							
1. Development cost	0.05	4	4	3	0.2	0.2	0.15
2. Market penetration rate	0.2	5	3	4	1	0.6	0.8
3. Expected lifecycle	0.05	4	5	3	0.2	0.25	0.15
Total	**1**	**32**	**29**	**26**	**4.8**	**3.85**	**4**

The results of the competitiveness analysis show that the importance of using the SiC powder coated Zirconium alloy is a very important in the nuclear energy plants, due to marketing rate criteria comparing that Zirconium alloy which consider the competitive material to SiC in cladding manufacturing due to its advantages such as high melting point, lower rate of hydrogen formation as a result of reaction with water at high temperatures, high corrosion resistance. Therefore, the SiC is promising material which will utilize in reactor with high thermal efficiency and low cost.

4.2 SWOT analysis

Complex analysis solution with the greatest competitiveness is carried out with the method of the SWOT analysis: Strengths, Weaknesses, Opportunities and Threats. The analysis has several stages. The first stage consists of describing the strengths and weaknesses of the project, identifying opportunities and threats to the project that have emerged or may appear in its external environment. The second stage consists of identifying the compatibility of the strengths and weaknesses of the project with the external environmental conditions. This compatibility or incompatibility should help to identify what strategic changes are needed.

Table 4.2 – SWOT analysis.

	Strengths: S1. High melting point, low-density material, and less waste disposal restrictions S2. Slow rate of hydrogen generation from reaction with water at high temperatures S3. High corrosion resistance and low neutron absorption cross-section	**Weaknesses:** W1. highly covalent (up to 88%) chemical bonding between silicon and carbon atoms lead to manufacture by difficult techniques W2. Lack information about wetting properties. W3. New material therefore it needs to high marketing and wide spreading
Opportunities: O1. Saving thermal energy O2. Decreasing capital cost O3. Increasing efficiency of heat transfer	It becomes one of solution to overcome many problems which face nuclear manufacturing and design. it increases the power and efficiency of NPP. It allows manufacturing variety as a result low cost.	It leads to delay the manufacturing procedures due to ensure increasing the information about it. It leads to manufacturing defects. It leads to take long time to marketing distribution.
Threats: T1. Natural catastrophes T2. Calculations mistakes during implementation	It leads to increase safety and protection criteria. It leads to motivate to mass production with high quality and quantity.	It leads to using it with high limitation applications which are far from any natural disasters.

T3. Changing its properties during operation due to neutrons radiation	It leads to increase the lifetime and expiration dates	It leads to manufacture it under high supervision from authorized sides.

4.3 Project Initiation

The initiation process group consists of processes that are performed to define a new project or a new phase of an existing one. In the initiation processes, the initial purpose and content are determined, and the initial financial resources are fixed. The internal and external stakeholders of the project who will interact and influence the overall result of the research project are determined.

4.3.1 Project stakeholders and participants include

Table 4.3 – Stakeholders of the project.

Project stakeholders	**Stakeholder expectations**
Nuclear industry organizations	Increasing the lifetime of SiC as a cladding and ensuring high thermal and mechanical efficiency. Market competitiveness against Zirconium alloy.

4.3.2 Objectives and outcomes of the project

Table 4.4 – Purpose and results of the project.

Purpose of project:	Design and production two substrates of SiC one of them coated on zirconium in air environment, and the second coated on zirconium in argon chamber and study their mechanical properties for using them as a cladding in LWR.
Expected results of the project:	High thermal and mechanical efficiency, increasing the expiring dates of reactor cladding as a result save money and energy.
Criteria for acceptance of the project result:	The project has all criteria and qualifications which are required such as high reliability, safety and lifetime as well, it has high saving to energy

Requirements for the project result:	It has to take suitable time for the manufacturing procedures to ensure increasing the scientific information by developing the research about it and make precise calculations.
	It has to avoid manufacturing defects and ensure the standard safety and quality criteria.
	It has to work in highly marketing distribution by making broad announcements to avoid poor storage.

The organizational structure of the project

It is necessary to solve some questions: who part of the working group of this project will be, determine the role of each participant in this project, and prescribe the functions of the participants and their number of labor hours in the project.

Table 4.5 – Structure of the project.

№	Participant	Role in the project	Functions	Labor time, hours (working days (from table 4.7) × 6 hours) recalculate
1	Supervisor Professor, D. Sc. Andrey Lider Head of Division for Experimental Physics Tomsk Polytechnic University	Head of project	Creating the plan of work, managing the research process Verifying of work evolution through weekly meetings.	26 d * 6h =156h
2	MSc. Student (Engineer)	Executor	Conducting experiments, evaluating data, making graphs, analysis of the results.	75 d * 6h =450h
3	PhD. Student (Co Supervisor)	Executor	Conducting experiments, evaluating data, making graphs,	79 d * 6h =474h

			analysis of the results.	

Project limitations

Project limitations are all factors that can be as a restriction on the degree of freedom of the project team members.

Table 4.6 – Project limitations.

Factors	**Limitations / Assumptions**
3.1. Project's budget	264743.6
3.1.1. Source of financing	Internal TPU
3.2. Project timeline:	01.02.2021-28.05.2021
3.2.1. Date of approval of plan of project	17.02.2021
3.2.2. Completion date	21.05.2021

4.3.3 Project Schedule

As part of planning a science project, you need to build a project timeline and a Gantt Chart.

Table 4.7 – Project Schedule.

Job title	Duration, working days	Start date	Date of completion	Participants
Layout and objectives of project plan	4	01.02.2021	04.02.2021	S, Co S
Special literature selection and studying	15	05.02.2021	24.02.2021	S, E, Co S
Timetable development	2	25.02.2021	31.03.2021	S, E, Co S
literature discussion	3	01.03.2021	03.03.2021	S, E, Co S
Conducting experiments	18	04.03.2021	30.03.2021	E, Co S

Calculation of standard parameters	15	31.03.2021	21.04.2021	E, Co S
Analysis the data and discussion	20	22.04.2021	28.05.2021	E, Co S
Summarizing	2	01.06.2021	02.06.2021	S, E, Co S
Total sum:	79			

A Gantt chart, or harmonogram, is a type of bar chart that illustrates a project schedule. This chart lists the tasks to be performed on the vertical axis, and time intervals on the horizontal axis. The width of the horizontal bars in the graph shows the duration of each activity.

Table 4.8 – A Gantt charts.

№	Activities	Participants	T_c, days	Duration of the project											
				February			March			April			May		
				1	2	3	1	2	3	1	2	3	1	2	3
1	Layout and objectives of project plan	S, Co S	4	▨											
2	Special literature selection and studying	S, Co S, E	15	▨■	▨■										
3	Timetable development	S, Co S, E	2		▨■										
4	Literature discussion	S, Co S, E	3			▨■									
5	Conducting experiments	E, Co S	18			■	■	■							
6	Calculation of standard parameters	E, Co S	15					■	■	■					
7	Analysis the data and discussion	E, Co S	20								■	■	■	■	

8	Summarizing	S, Co S, E	2												■

Supervisor (S) & co supervisor (Co S) & Engineer – ▨

; Engineer (E) & co supervisor (Co S)– ■

4.4 Scientific and technical research budget

The amount of costs associated with the implementation of this work is the basis for the formation of the project budget. This budget will be presented as the lower limit of project costs when forming a contract with the customer.

To form the final cost value, all calculated costs for individual items related to the manager and the student are summed.

In the process of budgeting, the following grouping of costs by items is used:

- Material costs of scientific and technical research;
- costs of special equipment for scientific work (Depreciation of equipment used for design);
- basic salary;
- additional salary;
- labor tax;
- overhead.

4.4.1 Calculation of material costs

The calculation of material costs is carried out according to the formula:

$$C_m = (1 + k_T) \cdot \sum_{i=1}^{m} P_i \cdot N_{consi} \qquad (4.2)$$

where m – the number of types of material resources consumed in the performance of scientific research;

N_{consi} – the amount of material resources of the i-th species planned to be used when performing scientific research (units, kg, m, m^2, etc.);

P_i – the acquisition price of a unit of the i-th type of material resources consumed (rub. /units, rub. /kg, rub. /m, rub. /m^2, etc.);

k_T – coefficient taking into account transportation costs.

Prices for material resources can be set according to data posted on relevant websites on the Internet by manufacturers (or supplier organizations).

Table 4.9 – Material costs.

Name	Unit	Amount	Price per unit, rub	Material costs, rub.
A4 printer paper	pcs	1	300	300
Printer cartridge	pcs	1	2300	2300
Ballpoint pen	pcs	2	50	100
Pencil	pcs	1	60	60
Pencil grills	pcs	1	30	30
Drawing paper	pcs	6	15	90
Total				2880

4.4.2 Costs of special equipment

This point includes the costs associated with the acquirement of special equipment (instruments, stands, devices and mechanisms) necessary to carry out work on a specific topic.

Table 4.10 – Costs of special equipment (+software).

№	Equipment identification	Quantity of equipment	Price per unit, rub.	Total cost of equipment, rub.
1.	Laptop	1	30000	30000
	X-ray spectroscopy	1	1500000	1500000
	KB Hardwin XL indentation setup	1	740000	740000
	IPG Photonics	1	500000	500000
	SIKA DENSITEC L	1	10000	10000
	Flexure-instorn	1	75000	75000

OR

Calculation of the depreciation. Depreciation is not charged if an equipment cost is less than 40 thousand rubles, its cost is taken into account in full.

If you use available equipment, then you need to calculate depreciation:

$$A = \frac{C * H_a}{100} \tag{4.3}$$

A - annual amount of depreciation;

C - initial cost of the equipment;

$\mathrm{H_a} = \frac{100}{\mathrm{T}}$ - rate of depreciation;

T - life expectancy.

Table 4.10 b – Depreciation of special equipment (+software).

№	equipment identification	Quantity of equipment	Total cost of equipment, rub.	Life expectancy, year	Working days	Depreciation for the duration of the project, rub.	Equipment prices which is not depreciated	
1.	*Computer*	1	30000	-	75	-	-	3000
2.	X-ray spectroscopy	1	1500000	20	5	205.5	1027.9	-
	KB Hardwin XL indentation setup	1	740000	10	5	202.7	1013.5	-
	IPG Photonics	1	500000	15	5	91.3	456.5	-
	SIKA DENSITEC L	1	10000	-	15	-	-	10000
	Flexure-instorn	1	750000	10	5	205.5	1027.5	-
Total						13525		

4.4.3 Basic salary

This point includes the basic salary of participants directly involved in the implementation of work on this research. The value of salary costs is determined based on the labor intensity of the work performed and the current salary system

The basic salary (S_b) is calculated according to the formula:

$$S_{\text{b}} = S_a \cdot T_{\text{w}} \qquad (4.4)$$

where Sb – basic salary per participant;

T_{w} – the duration of the work performed by the scientific and technical worker, working days;

S_d - the average daily salary of a participant, rub.

The average daily salary is calculated by the formula:

$$S_d = \frac{S_m \cdot M}{F_{\text{v}}} \qquad (4.5)$$

where S_m – monthly salary of a participant, rub.;

M – the number of months of work without leave during the year:

at holiday in 48 days, M = 11.2 months, 6 day per week;

F_v– valid annual fund of working time of scientific and technical personnel (251 days).

Table 4.11 – The valid annual fund of working time.

Working time indicators	
Calendar number of days	365
The number of non-working days - weekend - holidays	 52 14
Loss of working time - vacation - isolation period - sick absence	 48
The valid annual fund of working time	251

Monthly salary is calculated by formula:

$$S_{month} = S_{base} \cdot (k_{premium} + k_{bonus}) \cdot k_{reg} \tag{4.6}$$

where S_{base} – base salary, rubles;

$k_{premium}$ – premium rate;

k_{bonus} – bonus rate;

k_{reg} – regional rate.

Table 4.12 – Calculation of the base salaries.

Performers	S_{base}, rubles	$k_{premium}$	k_{bonus}	k_{reg}	S_{month}, rub.	W_d, rub.	T_p, workdays (from table 4.7)	W_{base}, rub.
Supervisor	36174	-	-	1,3	47026.2	2098.4	26	54558.4
Engineer 1	18426				23953.8	1068.9	75	80167.5
Engineer 2	20685				26890.5	1222.3	79	96561.3
Total					231287.2			

4.4.4 Labor tax

Tax to extra-budgetary funds are compulsory according to the norms established by the legislation of the Russian Federation to the state social insurance (SIF), pension fund (PF) and medical insurance (FCMIF) from the costs of workers.

Payment to extra-budgetary funds is determined of the formula:

$$P_{social} = k_b \cdot (W_{base} + W_{add}) \tag{4.7}$$

where k_b – coefficient of deductions for labor tax.

In accordance with the Federal law of July 24, 2009 No. 212-FL, the amount of insurance contributions is set at 30%. Institutions conducting educational and scientific activities have rate - 27.1%.

Table 4.13 – Labor tax.

	Project leader	**Engineer(1+1)**
Coefficient of deductions	0.271	
Salary (basic and additional), rubles	54558.4	176728.3
Labor tax, rubles	14785.3	47893.4
Total	62678.7	

4.4.5 Overhead costs

Overhead costs include other management and maintenance costs that can be allocated directly to the project. In addition, this includes expenses for the maintenance, operation and repair of equipment, production tools and equipment, buildings, structures, etc.

Overhead costs account from 30% to 90% of the amount of base and additional salary of employees.

Overhead is calculated according to the formula:

$$C_{ov} = k_{ov} \cdot (W_{base} + W_{add}) \tag{4.8}$$

where k_{ov} – overhead rate.

Table 4.14 – Overhead.

	Project leader	**Engineers (2)**
Overhead rate	0.7	
Salary, rubles	54558.4	176728.3
Overhead, rubles	38190.9	123709.8
Total	161900.7	

4.4.6 Other direct costs

Energy costs for equipment are calculated by the formula:

$$C = P_{el} \cdot P \cdot F_{eq}$$

where P_{el} – power rates (5.8 rubles per 1 kWh);

P – power of equipment, kW;

F_{eq} – equipment usage time, hours.

It is considered that all equipment has the same power (kw) for approximation.

Laptop

$C = P_{el} \cdot P \cdot F_{eq} = 5.8 \cdot 0.08 \cdot 564 \approx 262$ rub.

Telecentric pipe with light source

$C = P_{el} \cdot P \cdot F_{eq} = 5.8 \cdot 0.08 \cdot 132 \approx 62$ rub.

Syringe pump

$C = P_{el} \cdot P \cdot F_{eq} = 5.8 \cdot 0.08 \cdot 132 \approx 62$ rub.

Photo camera

$C = P_{el} \cdot P \cdot F_{eq} = 5.8 \cdot 0.08 \cdot 132 \approx 62$ rub.

High speed video camera

$C = P_{el} \cdot P \cdot F_{eq} = 5.8 \cdot 0.08 \cdot 132 \approx 62$ rub.

Heater

$C = P_{el} \cdot P \cdot F_{eq} = 5.8 \cdot 0.08 \cdot 132 \approx 62$ rub.

Total power consumption for equipment = 262 + (5*62) = 572 rub

4.4.7 Formation of budget costs

The calculated cost of research is the basis for budgeting project costs. Determining the budget for the scientific research is given in the table 4.15.

Table 4.15 – Items expenses grouping.

Name	**Cost, rubles**
1. Material costs	2880
2. Equipment costs	13525
3. Basic salary	231287.2

4. Additional salary	0
5. Labor tax	62678.7
6. Overhead	161900.7
7. Other direct costs	572
Total planned costs	**264743.6**

4.5 Evaluation of the comparative effectiveness of the project

Determination of efficiency is based on the calculation of the integral indicator of the effectiveness of scientific research. Its finding is associated with the definition of two weighted average values: financial efficiency and resource efficiency.

The integral indicator of the financial efficiency of a scientific study is obtained in the course of estimating the budget for the costs of three (or more) variants of the execution of a scientific study. For this, the largest integral indicator of the implementation of the technical problem is taken as the calculation base (as the denominator), with which the financial values for all the options are correlated.

The integral financial measure of development is defined as:

$$I_f^d = \frac{C_i}{C_{\max}} \tag{4.9}$$

where I_f^d – integral financial measure of development;

C_i – the cost of the i-th version;

$C_{\max}$ – the maximum cost of execution of a research project (including analogues).

The obtained value of the integral financial measure of development reflects the corresponding numerical increase in the budget of development costs in times (the value is greater than one), or the corresponding numerical reduction in the cost of development in times (the value is less than one, but greater than zero).

Since the development has one performance, then I_f^d = 1.

The integral indicator of the resource efficiency of the variants of the research object can be determined as follows:

$$I_m^a = \sum_{i=1}^{n} a_i b_i^a \qquad I_m^p = \sum_{i=1}^{n} a_i b_i^p$$

where I_m– integral indicator of resource efficiency for the i-th version of the development;

a_i– the weighting factor of the i-th version of the development;

b_i^a, b_i^p – score rating of the i-th version of the development, is established by an expert on the selected rating scale;

n – number of comparison parameters.

The calculation of the integral indicator of resource efficiency is presented in the form of table 4.16.

Table 4.16 – Evaluation of the performance of the project.

Criteria	**Weight criterion**	**Points**	
		SiC	**Zr-alloy**
1. Energy efficiency	0.1	5	4
2. Reliability	0.2	5	3
3. Safety	0.1	4	3
4. Functional capacity	0.3	5	4
Economic criteria for performance evaluation			
1. The cost of development	0.05	4	4
2. Market penetration rate	0.2	5	3
3. Expected life	0.05	4	3
Total	1	32	24

The integral indicator of the development efficiency (I_e^p) is determined on the basis of the integral indicator of resource efficiency and the integral financial indicator using the formula:

$$I_e^p = \frac{I_m^p}{I_f^d};\ I_e^a = \frac{I_m^a}{I_f^a}. \tag{4.10}$$

Comparison of the integral indicator of the current project efficiency and analogues will determine the comparative efficiency. Comparative effectiveness of the project:

$$E_c = \frac{I_e^p}{I_e^a} = \frac{4.75}{4.1} \approx 1.28. \tag{4.11}$$

Thus, the effectiveness of the development is presented in table 4.17.

Table 4.17 – Efficiency of development

№	**Indicators**	**Points**	
		Zr-1Nb	**Zr-2.5Nb**
1	Integral financial measure of development	1	1
2	Integral indicator of resource efficiency of development	4.75	3.7
3	Integral indicator of the development efficiency	4.75	3.7

Comparison of the values of integral performance indicators allows us to understand and choose a more effective solution to the technical problem from the standpoint of financial and resource efficiency.

4.6 Conclusion

Thus, in this part was developed stages for design and create competitive development that meet the requirements in the field of resource efficiency and resource saving.

These stages include:

- development of a common economic project idea, formation of a project concept;

- organization of work on a research project;
- identification of possible research alternatives;
- research planning;
- assessing the commercial potential and prospects of scientific research from the standpoint of resource efficiency and resource saving;
- determination of resource (resource saving), financial, budget, social and economic efficiency of the project.

As a result, the current project is more competitive from the point of reliability and safety. The competitiveness of project is higher than competitor’s option. The budget of the project equals **264743.6** rubles and integrating efficiency indicator is 1.28 times greater in comparison with the competitor, and it has a value 4.75.

Chapter 5- Social responsibility

5.1 Introduction

The main purpose of this research work is to develop the various technologies around silicon carbides to make it more acceptable as cladding material for the next generation of nuclear reactors. From the numerous discussions below, silicon carbide has some special properties that can be comparable above the existing fuel cladding material, which is zirconium. Despite zirconium-based alloys has gain recognition over its predecessor stainless steel from the first generation of reactors to the third generations, improvements need to be done through research and development to welcome the third generation plus and the fourth generation of nuclear reactors. There are so many ongoing research and development towards the generation (IV) reactors in which the nuclear fuel cladding material is one of the central concern due to the operational conditions of these reactors.

This study aimed to investigate some mechanical enduring characteristics of the coating to be established where SiC will be deposited on Zr-1Nb alloy using the Selective Laser Sintering (SLS) technique, an Additive Manufacturing (AM) 3D printing approach. This study is focused on designing nuclear fuel cladding component which could be applicable under extreme temperature conditions in order to limit issues encountered when zirconium-alloys are used directly and to ensure cladding integrity in future LWR cladding components.

5.2 Legal and organizational items in providing safety

Nowadays one of the main ways to radical improvement of all prophylactic work referred to reduce Total Incidents Rate and occupational morbidity is the widespread implementation of an integrated Occupational Safety and Health management system. That means combining isolated activities into a single system of targeted actions at all levels and stages of the production process.

Occupational safety is a system of legislative, socio-economic, organizational, technological, hygienic and therapeutic and prophylactic measures and tools that ensure the safety, preservation of health and human performance in the work process [1].

According to the Labor Code of the Russian Federation, every employee has the right:

- to have a workplace that meets Occupational safety requirements;

- to have a compulsory social insurance against accidents at manufacturing and occupational diseases;

- to receive reliable information from the employer, relevant government bodies and public organizations on conditions and Occupational safety at the workplace, about the existing risk of damage to health, as well as measures to protect against harmful and (or) hazardous factors;

- to refuse carrying out work in case of danger to his life and health due to violation of Occupational safety requirements;

- be provided with personal and collective protective equipment in compliance with Occupational safety requirements at the expense of the employer;

- for training in safe work methods and techniques at the expense of the employer;

- for personal participation or participation through their representatives in consideration of issues related to ensuring safe working conditions in his workplace, and in the investigation of the accident with him at work or occupational disease;

- for extraordinary medical examination in accordance with medical recommendations with preservation of his place of work (position) and secondary earnings during the passage of the specified medical examination;

- for warranties and compensation established in accordance with this Code, collective agreement, agreement, local regulatory an act, an employment contract, if he is engaged in work with harmful and (or) hazardous working conditions.

The labor code of the Russian Federation states that normal working hours may not exceed 40 hours per week, the employer must keep track of the time worked by each employee.

Rules for labor protection and safety measures are introduced in order to prevent accidents, ensure safe working conditions for workers and are mandatory for workers, managers, engineers and technicians.

5.3 Basic ergonomic requirements for the correct location and arrangement of researcher’s workplace

The workplace when working with a PC should be at least 6 square meters. The legroom should correspond to the following parameters: the legroom height is at least 600 mm, the seat distance to the lower edge of the working surface is at least 150 mm, and the seat height is 420 mm. It is worth noting that the height of the table should depend on the growth of the operator.

The following requirements are also provided for the organization of the workplace of the PC user: The design of the working chair should ensure the maintenance of a rational working posture while working on the PC and allow the posture to be changed in order to reduce the static tension of the neck and shoulder muscles and back to prevent the development of fatigue.

The type of working chair should be selected taking into account the growth of the user, the nature and duration of work with the PC. The working chair should be lifting and swivel, adjustable in height and angle of inclination of the seat and back, as well as the distance of the back from the front edge of the seat, while the adjustment of each parameter should be independent, easy to carry out and have a secure fit.

5.4 Occupational safety

A dangerous factor or industrial hazard is a factor whose impact under certain conditions leads to trauma or other sudden, severe deterioration of health of the worker [87].

A harmful factor or industrial health hazard is a factor, the effect of which on a worker under certain conditions leads to a disease or a decrease in working capacity.

5.4.1 Analysis of harmful and dangerous factors that can create object of investigation

The object of investigation is silicon carbide coating. Therefore, the object of investigation cannot cause harmful and dangerous factors. Mechanical and Adhesion Evaluation of SiC Sintered coating on Zr-1Nb Substrates Fabricated Using Selective Laser Sintering Technique; powder of SiC was sintered on Zr-1Nb samples substrate with technique of SLS. Two samples were coated with 200 μm in different atmospheres (Air and Ar), by using mechanical investigations such as, micro indentation, scratch adhesion, and tribological tests, the surface profile of coating uniformity were investigated, the results achieved, products have not effect on the personnell, structures, and environment. the cost is lower than cost of accident.

5.4.2. Analysis of harmful and dangerous factors that can arise at workplace during investigation

The working conditions in the workplace are characterized by the presence of hazardous and harmful factors, which are classified by groups of elements: physical, chemical, biological, psychophysiological. The main elements of the production process that form dangerous and harmful factors are presented in Table 5.1.

Table 5.1 – Possible hazardous and harmful factors.

Factors (GOST 12.0.003-2015)	Work stages			Legal documents
	Development	Manufacture	Exploitation	
1. Deviation of microclimate indicators	+	+	+	Sanitary rules 2.2.2 / 2.4.1340–03. Sanitary and
2. Excessive noise		+		

3. Increased level of electromagnetic radiation		+		epidemiological rules and regulations "Hygienic requirements for personal electronic computers and work organization." Sanitary rules 2.2.1 / 2.1.1.1278–03. Hygienic requirements for natural, artificial and combined lighting of residential and public buildings. Sanitary rules 2.2.4 / 2.1.8.562–96. Noise at workplaces, in premises of residential, public buildings and in the construction area. Sanitary rules 2.2.4.548–96. Hygienic requirements for the
4. Insufficient illumination of the working area		+	+	

				microclimate of industrial premises.
5. Abnormally high voltage value in the circuit, the closure which may occur through the human body	+	+	+	Sanitary rules GOST 12.1.038-82 SSBT. Electrical safety. Maximum permissible levels of touch voltages and currents.
Laser radiation				Laser safety. General safety requirements for development and operation of laser products. GOST 31581-2012

The following factors effect on person working on a computer:

- physical:
  - temperature and humidity;
  - noise;
  - static electricity;
  - electromagnetic field of low purity;
  - illumination;
  - presence of radiation;
- psychophysiological:
  - psychophysiological dangerous and harmful factors are divided into:
    - physical overload (static, dynamic)
    - mental stress (mental overstrain, monotony of work, emotional overload).
    -

5.4.2 a Deviation of microclimate indicators

The air of the working area (microclimate) is determined by the following parameters: temperature, relative humidity, air speed. The optimum and permissible values of the microclimate characteristics are established in accordance with [88] and are given in Table 5.2.

Table 5.2 – Optimal and permissible parameters of the microclimate.

Period of the year	Temperature, ^{C}	Relative humidity,%	Speed of air movement, m/s
Cold and changing of seasons	23-25	40-60	0.1
Warm	23-25	40	0.1

5.4.2b Excessive noise

Noise and vibration worsen working conditions, have a harmful effect on the human body, namely, the organs of hearing and the whole body through the central nervous system. It results in weakened attention, deteriorated memory, decreased response, and increased number of errors in work. Noise can be generated by operating equipment, air conditioning units, daylight illuminating devices, as well as spread from the outside. When working on a PC, the noise level in the workplace should not exceed 50 dB.

5.4.2 c Increased level of electromagnetic radiation

The screen and system blocks produce electromagnetic radiation. Its main part comes from the system unit and the video cable. According to [88], the intensity of the electromagnetic field at a distance of 50 cm around the screen along the electrical component should be no more than:

- in the frequency range 5 Hz - 2 kHz - 25 V / m;
- in the frequency range 2 kHz - 400 kHz - 2.5 V / m.

The magnetic flux density should be no more than:

- in the frequency range 5 Hz - 2 kHz - 250 nT;
- in the frequency range 2 kHz - 400 kHz - 25 nT.

5.4.2 d Abnormally high voltage value in the circuit

Depending on the conditions in the room, the risk of electric shock to a person increases or decreases. Do not operate the electronic device in conditions of high humidity (relative air humidity exceeds 75% for a long time), high temperature (more than 35 ° C), the presence of conductive dust, conductive floors and the possibility of simultaneous contact with metal components connected to the ground and the metal casing of electrical equipment. The operator works with electrical devices: a computer (display, system unit, etc.) and peripheral devices. There is a risk of electric shock in the following cases:

- with direct contact with current-carrying parts during computer repair;
- when touched by non-live parts that are under voltage (in case of violation of insulation of current-carrying parts of the computer);
- when touched with the floor, walls that are under voltage;
- short-circuited in high-voltage units: power supply and display unit.

Table 5.3 – Upper limits for values of contact current and voltage.

	Voltage, V	Current, mA
Alternate, 50 Hz	2	0.3
Alternate, 400 Hz	3	0.4
Direct	8	1.0

5.4.2 e Insufficient illumination of the working area

Light sources can be both natural and artificial. The natural source of the light in the room is the sun, artificial light are lamps. With long work in low illumination conditions and in violation of other parameters of the illumination, visual perception decreases, myopia, eye disease develops, and headaches appear.

According to the standard, the illumination on the table surface in the area of the working document should be 300-500 lux. Lighting should not create glare on the surface of the monitor. Illumination of the monitor surface should not be more than 300 lux.

The brightness of the lamps of common light in the area with radiation angles from 50 to 90° should be no more than 200 cd/m, the protective angle of the lamps should be at least 40°. The safety factor for lamps of common light should be assumed to be 1.4. The ripple coefficient should not exceed 5%.

5.4.2 f Laser radiation

Selective laser sintering (SLS) is a technique, which involves the use of additive manufacturing technology that uses laser to selectively sinter powder materials layer by layer in order to form a solid mass of 3D structure. It was developed and patented by Dr. Joseph Beaman and Dr. Carl Deckard of the University of Texas at Austin in 1980s [5]. SLS technology has been widely used in industry because of its capability to produce 3D complex-structure parts directly from the CAD model. In addition, compared to other additive manufacturing techniques, such as stereo-lithography (SLA) and fused deposition modeling (FDM), SLS process requires no supporting materials because the sintered part is surrounded and supported by un-sintered powder at all times, which allows for the construction of more 14 complex 3D structures. SLS process is capable of producing parts made from a wide variety of materials, including polymers, glasses, ceramics, and metals for rapid prototyping, and even rapid manufacturing of final products. The creation of complex geometries of SiC parts is possible, but with difficulties. It is possible to use indirect SLS methods to create SiC preforms from a powder mixture of SiC as structural material and with thermosetting polymers as binder material. These parts are further processed at elevated temperatures to carbonize the polymer binders followed by reactive infiltration of silicon to yield near-net shape parts. It is also possible to introduce the application of transient binders to infiltrate SLS-process polymer-SiC preforms in order to prevent shrinkage and collapse of the structure between softening and cross-linking of the initial polymer binders. This allows for support-free infiltration of SiC preforms with minimal deformation and shrinkage of the parts during the furnace sintering.

Regenfuss and Exner introduced laser micro sintering (LMS) in 2002, which is a modification of SLS process. This has been successfully employed in the creation of metallic micro parts. It involves the application of high-frequency pulsed laser, new powder and slurry coating system, and the proprietary CAD software. This technology has also been used to process non-metal materials, including oxide and non-oxide ceramics.

Laser safety refers to the safe design, operation and implementation of lasers to minimize the risk of laser accidents, especially those involving eye injuries.

The lasers are dangerous because a small amount of laser radiations can lead to serious and permanent eye injuries, the sale and usage of lasers is typically subject to government regulations.

Laser radiation was classified according to the power and the wavelength. These classifications help to manage and control the risk of laser injuries. The injuries could happen because of two main effects, firstly the thermal effect and secondly the photo chemical effect. Moderate and high-power lasers are potentially hazardous because they can burn the skin. While moderate laser power can cause eye injuries also the high-power laser can cause burn to the skin. Some recommendations must be followed to avoid the hazard during using laser radiation devices such as labeling lasers with specific warnings and wearing laser safety goggles when operating lasers [90].

Laser products are classified into four hazard classes depending on the radiation generated.

Class 1. Laser products that are safe under the intended operating conditions.

Class 2. Laser products that generate visible radiation in the wavelength range from 400 to 700 nm. Eye protection is provided by natural reactions, including the blink reflex.

Class 3A. Laser products are safe for viewing with the unprotected eye. For laser products emitting radiation in the wavelength range of 400 to 700 nm, protection is provided by natural reactions, including the blink reflex. For other wavelengths, the hazard to the unprotected eye is no greater than for class 1.

Direct observation of the beam emitted by Class 3A laser products with optical instruments (e.g. binoculars, telescope, microscope) can be hazardous.

Class 3B. Direct observation of such laser products is always dangerous. Visible scattered radiation is usually harmless.

Conditions for safe observation of diffuse reflection for laser products of class 3B in the visible area: the minimum distance for observation between the eye and the screen is 13 cm, the maximum observation time is 10 s.

Class 4. Laser products emitting hazardous stray radiation. They can cause skin damage and also create a fire hazard. Special care should be taken when using them.

In SLS system a Ytterbium green laser is being used with an output wavelength of 1070nm and a maximum power of 500W. In a manufacturing context, a laser power around 125W was used. Within a natural air, a substrate is considered to work at the time by carefully placing it in the chamber filled. In order to achieve sintering, the SiC powder then sintered with the heat generated by the laser on increasing the local layer temperature just below the melting point. The laser heats the SiC particles in specified directions until it is completely sintered through successive deposition [90].

5.4.3 Justification of measures to reduce the levels of exposure to hazardous and harmful factors on the researcher

5.4.3 a Deviation of microclimate indicators

The measures for improving the air environment in the production room include: the correct organization of ventilation and air conditioning, heating of room. Ventilation can be realized naturally and mechanically. In the room, the following volumes of outside air must be delivered:

- at least 30 m ^{3} per hour per person for the volume of the room up to 20 m ^{3} per person;

- natural ventilation is allowed for the volume of the room more than 40 m ^{3} per person and if there is no emission of harmful substances.

The heating system must provide sufficient, constant and uniform heating of the air. Water heating should be used in rooms with increased requirements for clean air.

The parameters of the microclimate in the laboratory regulated by the central heating system, have the following values: humidity 40%, air speed 0.1 m / s, summer temperature 20-25 ° C, in winter 13-15 ° C. Natural ventilation is provided in the laboratory. Air enters and leaves through the cracks, windows, doors. The main disadvantage of such ventilation is that the fresh air enters the room without preliminary cleaning and heating.

5.4.3 b Excessive noise

In research audiences, there are various kinds of noises that are generated by both internal and external noise sources. The internal sources of noise are working equipment, personal computer, printer, ventilation system, as well as computer equipment of other engineers in the audience. If the maximum permissible conditions are exceeded, it is sufficient to use sound-absorbing materials in the room (sound-absorbing wall and ceiling cladding, window curtains). To reduce the noise penetrating outside the premises, install seals around the perimeter of the doors and windows.

5.4.3 c Increased level of electromagnetic radiation

There are the following ways to protect against EMF:

- increase the distance from the source (the screen should be at least 50 cm from the user);
- the use of pre-screen filters, special screens and other personal protective equipment.

When working with a computer, the ionizing radiation source is a display. Under the influence of ionizing radiation in the body, there may be a violation of normal blood coagulability, an increase in the fragility of blood vessels, a decrease in immunity, etc. The dose of irradiation at a distance of 20 cm to the display is 50 µrem / hr. According to the norms [88], the design of the computer should provide the power of the exposure dose of x-rays at any point at a distance of 0.05 m from the screen no more than 100 µR / h.

Fatigue of the organs of vision can be associated with both insufficient illumination and excessive illumination, as well as with the wrong direction of light.

5.4.3 d Abnormally high voltage value in the circuit

Measures to ensure the electrical safety of electrical installations:

- disconnection of voltage from live parts, on which or near to which work will be carried out, and taking measures to ensure the impossibility of applying voltage to the workplace;
- posting of posters indicating the place of work;
- electrical grounding of the housings of all installations through a neutral wire;
- coating of metal surfaces of tools with reliable insulation;
- inaccessibility of current-carrying parts of equipment (the conclusion in the case of electroporating elements, the conclusion in the body of current-carrying parts) [89].

5.4.3 e Insufficient illumination of the working area

Desktops should be placed in such a way that the monitors are oriented sideways to the light openings, so that natural light falls mainly on the left.

Also, as a means of protection to minimize the impact of the factor, local lighting should be installed due to insufficient lighting, window openings should be equipped with adjustable devices such as blinds, curtains, external visors, etc.

5.4.4 General Laser Safety

1- Only trained, authorized personnel may operate lasers. Training is to be documented for each employee.

2- NEVER put yourself into any position where your eyes approach the axis of a laser beam (even with eye protection on).

3- Keep beam paths below or above standing or sitting eye level. Do not direct them towards other people.

4- Do not damage laser protective housings or defeat the interlocks on these housings.

5- Eliminate all reflective material from the vicinity of the beam paths.

6- Never use viewing instruments to look directly into a laser beam or its specular reflection. If this is necessary, install an appropriate filter into the optical element assembly.

7- Keep ambient light levels as high as operations will permit.

8- Follow departmental rules when performing high power laser operations after normal working hours.

9- Visitors should not be permitted to observe a laser experiment without first receiving a laser safety briefing and being issued laser eye protection. They will be escorted by knowledgeable personnel at all times.

5.4.4a Class 3b Requirements

1. Doors must be closed and locked during laser operations.

2. Doors must be properly posted, and the warning light energized during operations.

3. Door windows and labs windows must be covered to prevent the escape of a laser beam, unless an interlocked laser beam path enclosure is provided.

4. Do not aim the laser at an individual’s eyes.

5. Permit only properly trained and authorized personnel to operate the laser.

6. Enclose as much of the beam path as possible.

7. Place appropriate beam stops at the end(s) of the useful beam path(s).

8. Restrict the access of unauthorized personnel: control spectators.

9. Operate the laser in a controlled area in the SOP)

10. Employ a warning light or buzzer to indicated laser operation if appropriate, especially for invisible (UV or IR) lasers.

11. Locate the plane of the laser beam & associated optical devices well above or below the eye level of the observers whenever possible.

12. Firmly mount the laser to ensure the beam does not stray from the intended path.

13. Use proper eye protection if eye exposure to the direct beam or a specular reflection is possible.

14. Do not view the beam or its specular reflection with collecting optics without sufficient eye protection.

15. Remove all unnecessary reflective surfaces from the area of the beam path.

16. Should develop SOP for laser operation.

5.4.4b Class 4 Requirements (includes all Class 3b requirements and the following)

1. Develop SOP’s for laser operation.

2. Incorporate key control of master switch that can terminate beam operations.

3. Establish entryway safety controls to allow both rapid egress by laser personnel at all times and admittance to the controlled area under emergency conditions.

4. Provide for and ensure use of proper eye protection for everyone within the controlled area.

5. Use appropriate shielding between personnel and any beam having sufficient irradiance to pose a serious skin or fire hazard.

6. Use remote viewing methods where feasible (e.g. video monitoring) to accomplish any necessary viewing of the beam.

7. Construct non-specular absorbent beam stops of fire resistant materials.

8. Use adequate ventilation and vented enclosures when dealing with excimer lasers due to the presence of toxic gases and fumes.

9. Use proper window coverings for exterior windows and door windows as needed.

5.5 Ecological safety

5.5.1 Analysis of the impact of the nuclear power plant on the environment

Most nuclear power plants release gaseous and liquid radiological effluents into the environment, which must be monitored. Civilians living within 80 km of a nuclear power plant typically receive about 0.1 μSv per year.

All reactors are required to have a containment building in according to international requirements. The walls of containment buildings are several feet thick and made of concrete and therefore can stop the release of any radiation emitted by the reactor into the environment.

Large volumes of water are used during the process of nuclear power generation. The uranium fuel inside reactors undergoes induced nuclear fission which releases great amounts of energy that is used to heat water. The water turns into steam and rotates a turbine, creating electricity. Nuclear plants are built near bodies of water.

All possible impact of nuclear power plant on environment is greatly reduced in operating regime by many safety precautions means. The most danger of nuclear energy come because of different sorts of disaster.

5.5.2 Analysis of the environmental impact of the research process

Process of investigation itself in the thesis do not have essential effect on environment. One of hazardous waste is fluorescent lamps. Mercury in fluorescent lamps is a hazardous substance and its improper disposal greatly poisons the environment.

Outdated devices go to an enterprise that has the right to process wastes. It is possible to isolate precious metals with a purity in the range of 99.95–99.99% from computer components. A closed production cycle consists of the following stages: primary sorting of equipment; the allocation of precious, ferrous and non-ferrous metals and other materials; melting; refining and processing of metals. Thus, there is an effective disposal of computer devices.

5.5.3 Justification of environmental protection measures

Pollution reduction is possible due to the improvement of devices that produces electricity, the use of more economical and efficient technologies, the use of new methods for generating electricity and the introduction of modern methods and methods for cleaning and neutralizing industrial waste. In addition, this problem should be solved by efficient and economical use of electricity by consumers themselves. This is the use of more economical devices, as well as efficient regimes of these devices. This also includes compliance with production discipline in the framework of the proper use of electricity.

Simple conclusion is that it is necessary to strive to reduce energy consumption, to develop and implement systems with low energy consumption. In modern computers, modes with reduced power consumption during long-term idle are widely used.

5.6 Safety in emergency

5.6.1 Analysis of probable emergencies that may occur at the workplace during research

The fire is the most probable emergency in our life. Possible causes of fire:

- malfunction of current-carrying parts of installations;
- work with open electrical equipment;
- short circuits in the power supply;
- non-compliance with fire safety regulations;
- presence of combustible components: documents, doors, tables, cable insulation, etc.

Activities on fire prevention are divided into: organizational, technical, operational and regime.

5.6.2 Substantiation of measures for the prevention of emergencies and the development of procedures in case of emergencies

Organizational measures provide for correct operation of equipment, proper maintenance of buildings and territories, fire instruction for workers and employees, training of production personnel for fire safety rules, issuing instructions, posters, and the existence of an evacuation plan.

The technical measures include compliance with fire regulations, norms for the design of buildings, the installation of electrical wires and equipment, heating, ventilation, lighting, the correct placement of equipment.

The regime measures include the establishment of rules for the organization of work, and compliance with fire-fighting measures. To prevent fire from short circuits, overloads, etc., the following fire safety rules must be observed:

- elimination of the formation of a flammable environment (sealing equipment, control of the air, working and emergency ventilation);
- use in the construction and decoration of buildings of non-combustible or difficultly combustible materials;
- the correct operation of the equipment (proper inclusion of equipment in the electrical supply network, monitoring of heating equipment);
- correct maintenance of buildings and territories (exclusion of the source of ignition - prevention of spontaneous combustion of substances, restriction of fireworks);
- training of production personnel in fire safety rules;
- the publication of instructions, posters, the existence of an evacuation plan;
- compliance with fire regulations, norms in the design of buildings, in the organization of electrical wires and equipment, heating, ventilation, lighting;
- the correct placement of equipment;
- well-time preventive inspection, repair and testing of equipment.

In the case of an emergency, it is necessary to:

- inform the management (duty officer);
- call the Emergency Service or the Ministry of Emergency Situations - tel. 112;
- take measures to eliminate the accident in accordance with the instructions.

5.7 Conclusions

In this part of social responsibility, the hazardous and harmful factors were revealed. All necessary safety measures and precaution to minimize probability of accidents and traumas during investigation are given.

Possible negative effect on environment were given in compact form describing main ecological problem of using nuclear energy.

It could be stated that with respect to all regulations and standards, investigation itself and object of investigation do not pose special risks to personnel, other equipment and environment.

References

1. Padture, N. P., Gell, M., & Jordan, E. H. (2002). Thermal barrier coatings for gas-turbine engine applications. Science, 296(5566), 280-284.
2. Lima, R. S., & Marple, B. R. (2007). Thermal spray coatings engineered from nanostructured ceramic agglomerated powders for structural, thermal barrier and biomedical applications: a review. Journal of Thermal Spray Technology, 16(1), 40-63.
3. Wood, R. J. (2007). Tribo-corrosion of coatings: a review. Journal of Physics D: Applied Physics, 40(18), 5502.
4. PalDey, S., & Deevi, S. C. (2003). Properties of single layer and gradient (Ti, Al) N coatings. Materials Science and Engineering: A, 361(1-2), 1-8.
5. Valli, J. (1986). A review of adhesion test methods for thin hard coatings. Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 4(6), 3007-3014.
6. Mittal, K. L. (1976). Adhesion measurement of thin films. Electrocomponent science and technology, 3(1), 21-42.
7. Lin, C. K., & Berndt, C. C. (1994). Measurement and analysis of adhesion strength for thermally sprayed coatings. Journal of Thermal Spray Technology, 3(1), 75-104.
8. Hull, T. R., Colligon, J. S., & Hill, A. E. (1987). Measurement of thin film adhesion. Vacuum, 37(3-4), 327-330.
9. Jiang, L., & Cheung, R. (2009). A review of silicon carbide development in MEMS applications. International Journal of Computational Materials Science and Surface Engineering, 2(3-4), 227-242.
10. Zorman, C. A., & Parro, R. J. (2008). Micro-and nanomechanical structures for silicon carbide MEMS and NEMS. physica status solidi (b), 245(7), 1404-1424.
11. Zhao, N. (2017). Micro selective laser sintering of silicon carbide (Doctoral dissertation).
12. Cheung, R. (2006). Silicon carbide microelectromechanical systems for harsh environments. World Scientific.

13. Suasmoro, S., Pratapa, S., Hartanto, D., Setyoko, D., & Dani, U. M. (2000). The characterization of mixed titanate Ba1− xSrxTiO3 phase formation from oxalate coprecipitated precursor. Journal of the European Ceramic Society, 20(3), 309-314.
14. Khairnar, R. S., Narwade, V. N., & Kokol, V. (2018). Nanostructured bioceramics and applications. Fundamental Biomaterials: Ceramics, 251-263.
15. Philipp, H. R., & Taft, E. A. (1960). Silicon Carbide—A High Temperature Semiconductor. In Proceedings of the Conference on Silicon Carbide (p. 366). Pergamon Press Oxford, London, Paris, New York.
16. Harris, G. L. (Ed.). (1995). Properties of silicon carbide (No. 13). Iet.
17. Biedermann, E. (1965). The optical absorption bands and their anisotropy in the various modifications of SiC. Solid State Communications, 3(10), 343-346.
18. Choyke, W. J., Hamilton, D. R., & Patrick, L. (1964). Optical properties of cubic SiC: luminescence of nitrogen-exciton complexes, and interband absorption. Physical Review, 133(4A), A1163.
19. Solangi, A., & Chaudhry, M. I. (1992). Absorption coefficient of β–SiC grown by chemical vapor deposition. Journal of materials research, 7(3), 539-541.
20. Nishino, S., Matsunami, H., & Tanaka, T. (1978). Growth and morphology of 6H-SiC epitaxial layers by CVD. Journal of Crystal Growth, 45, 144-149.
21. Baumann Jr, H. N. (1952). The relationship of alpha and beta silicon carbide. Journal of The Electrochemical Society, 99(3), 109.
22. Abdelhafeez, A. M., Abouelsoud, A. A., Ashour, I., & AboBeah, R. (2021). SIMULATION OF THE DIRECT CARBOTHERMAL REDUCTION OF SiO2 FOR Si METAL USING MATLAB® AND ASPEN-HYSYS®. Journal of Advanced Engineering Trends, 40(1), 33-48.
23. Casady, J. B., & Johnson, R. W. (1996). Status of silicon carbide (SiC) as a wide-bandgap semiconductor for high-temperature applications: A review. Solid-State Electronics, 39(10), 1409-1422.
24. Greskovich, C., & Rosolowski, J. H. (1976). Sintering of covalent solids. Journal of the American Ceramic Society, 59(7-8), 336-343.

25. Ramanatahan, S., Prasad, R., & Gupta, C. K. (1990). Effect of Boron, Boron Carbide and Alumina Additions on the Sintering of Silicon Carbide. Transactions of the Indian Ceramic Society, 49(4), 77-81.
26. Coble, R. L. (1961). Sintering crystalline solids. I. Intermediate and final state diffusion models. Journal of applied physics, 32(5), 787-792.
27. Kingery, W. D., & Berg, M. (1955). Study of the initial stages of sintering solids by viscous flow, evaporation-condensation, and self-diffusion. Journal of Applied Physics, 26(10), 1205-1212.
28. Wilder, D. R., & Fitzsimmons, E. S. (1955). Further study of sintering phenomena. Journal of the American Ceramic Society, 38(2), 66-71.
29. Coble, R. L., & Cannon, R. M. (1978). Current paradigms in powder processing. In Processing of crystalline ceramics (pp. 151-170). Springer, Boston, MA.
30. Hansen, J. D., Rusin, R. P., Teng, M. H., & Johnson, D. L. (1992). Combined-stage sintering model. Journal of the American Ceramic Society, 75(5), 1129-1135.
31. Kraft, T., & Riedel, H. (2004). Numerical simulation of solid state sintering; model and application. Journal of the European Ceramic Society, 24(2), 345-361.
32. PROCHAZKA, S., & SCANLAN, R. M. (1975). Effect of boron and carbon on sintering of SiC. Journal of the American Ceramic Society, 58(1-2), 72-72.
33. Stobierski, L., & Gubernat, A. (2003). Sintering of silicon carbideI. Effect of carbon. Ceramics international, 29(3), 287-292.
34. Van Rijswijk, W., & Shanefield, D. J. (1990). Effects of carbon as a sintering aid in silicon carbide. Journal of the American Ceramic Society, 73(1), 148-149.
35. Noviyanto, A., & Yoon, D. H. (2013). Metal oxide additives for the sintering of silicon carbide: reactivity and densification. Current Applied Physics, 13(1), 287-292.
36. Perevislov, S. N. (2013). Mechanism of liquid-phase sintering of silicon carbide and nitride with oxide activating additives. Glass and ceramics, 70(7-8), 265-268.
37. Zhang, B. R., Marino, F., & Ferraris, M. (1994). Liquid-phase hot-pressing and WC-particle reinforcement of SiC-Si composites. Journal of the European Ceramic Society, 14(6), 549-555.

38. Lee, J. S., Lee, S. H., Nishimura, T., Hirosaki, N., & Tanaka, H. (2009). A ternary compound additive for vacuum densification of β-silicon carbide at low temperature. Journal of the European Ceramic Society, 29(16), 3419-3423.
39. Datta, M. S., Bandyopadhyay, A. K., & Chaudhuri, B. (2002). Sintering of nano crystalline α silicon carbide by doping with boron carbide. Bulletin of Materials Science, 25(3), 181-189.
40. She, J. H., & Ueno, K. (1999). Effect of additive content on liquid-phase sintering on silicon carbide ceramics. Materials Research Bulletin, 34(10-11), 1629-1636.
41. Omori, M., & Takei, H. (1982). Pressureless sintering of SiC. Journal of the American Ceramic Society, 65(6), c92-c92.
42. Lin, B. W., Imai, M., Yano, T., & Iseki, T. (1986). Hot-Pressing of β-SiC Powder with Al-B-C Additives. Journal of the American Ceramic Society, 69(4), C-67.
43. Zhou, Y., Tanaka, H., Otani, S., & Bando, Y. (1999). Low-temperature pressureless sintering of alpha-SiC with Al4C3-B4C-C additions. Journal of the American Ceramic Society, 82(8), 1959-1964.
44. Yonathan, P., Lee, J. H., Yoon, D. H., Kim, W. J., & Park, J. Y. (2009). Improvement of SiCf/SiC density by slurry infiltration and tape stacking. Materials Research Bulletin, 44(11), 2116-2122.
45. Huang, Z. H., Jia, D. C., Zhou, Y., & Liu, Y. G. (2003). A new sintering additive for silicon carbide ceramic. Ceramics International, 29(1), 13-17.
46. Yang, H., Zhang, L., Guo, X., Zhu, X., & Fu, X. (2011). Pressureless sintering of silicon carbide ceramics containing zirconium diboride. Ceramics International, 37(6), 2031-2035.
47. Sacks, M. D., Bozkurt, N., & Scheiffele, G. W. (1991). Fabrication of mullite and mullite-matrix composites by transient viscous sintering of composite powders. Journal of the American Ceramic Society, 74(10), 2428-2437.
48. Messner, R. P., & Chiang, Y. M. (1990). Liquid-phase reaction-bonding of silicon carbide using alloyed silicon-molybdenum melts. Journal of the American Ceramic Society, 73(5), 1193-1200.

49. Evans, R. S., Bourell, D. L., Beaman, J. J., & Campbell, M. I. (2003). Reaction bonded silicon carbide: SFF, process refinement and applications. In 2003 International Solid Freeform Fabrication Symposium.
50. Beaman, J. J., & Deckard, C. R. (1990). U.S. Patent No. 4,938,816. Washington, DC: U.S. Patent and Trademark Office.
51. Deckard, C. R., Beaman, J. J., & Darrah, J. F. (1992). U.S. Patent No. 5,155,324. Washington, DC: U.S. Patent and Trademark Office.
52. Nelson, J. C., Vail, N. K., Barlow, J. W., Beaman, J. J., Bourell, D. L., & Marcus, H. L. (1995). Selective laser sintering of polymer-coated silicon carbide powders. Industrial & engineering chemistry research, 34(5), 1641-1651.
53. Stevinson, B. Y., Bourell, D. L., & Beaman Jr, J. J. (2006, September). Support-free infiltration of selective laser sintered (SLS) silicon carbide preforms. In 2006 International Solid Freeform Fabrication Symposium.
54. Stierlen, P., & Eyerer, P. (1998). Si/SiC-Ceramtc prototypes via LS2 1-process (liquid silicon infiltration of laser sintered C-SiC parts). In 1999 International Solid Freeform Fabrication Symposium.
55. Exner, H., Horn, M., Streek, A., Ullmann, F., Hartwig, L., Regenfuß, P., & Ebert, R. (2008). Laser micro sintering: A new method to generate metal and ceramic parts of high resolution with sub-micrometer powder. Virtual and physical prototyping, 3(1), 3-11.
56. Regenfuss, P., Streek, A., Hartwig, L., Klötzer, S., Brabant, T., Horn, M., ... & Exner, H. (2007). Principles of laser micro sintering. Rapid Prototyping Journal.
57. Kruth, J. P., Wang, X., Laoui, T., & Froyen, L. (2003). Lasers and materials in selective laser sintering. Assembly Automation.
58. Mellali, M., Fauchais, P., & Grimaud, A. (1996). Influence of substrate roughness and temperature on the adhesion/cohesion of alumina coatings. Surface and coatings technology, 81(2-3), 275-286.
59. Singh, R. K., Gilbert, D. R., Fitz-Gerald, J., Harkness, S., & Lee, D. G. (1996). Engineered interfaces for adherent diamond coatings on large thermal-expansion coefficient mismatched substrates. Science, 272(5260), 396-398.

60. Sinnott, S. B., & Dickey, E. C. (2003). Ceramic/metal interface structures and their relationship to atomic-and meso-scale properties. Materials Science and Engineering: R: Reports, 43(1-2), 1-59.

61. Edition, F., & Ashby, M. F. (2011). MATERIAL SELECTION IN MECHANICAL DESIGN.

62. Terrani, K., Jolly, B., & Trammell, M. (2020). 3D printing of high-purity silicon carbide. Journal of the American Ceramic Society, 103(3), 1575-1581.

63. Birks, N., Meier, G. H., & Pettit, F. S. (2006). Introduction to the high temperature oxidation of metals. Cambridge university press.

64. Worch, H. (1989). P. Kofstad, High Temperature Corrosion. Elsevier Applied Science, London/New York 1988, 546 Seiten mit 222 Illustr. und 6 Tabellen,£ 68.00, ISBN 1-85166-154-9.

65. Chen, H., Wang, X., & Zhang, R. (2020). Application and development progress of Cr-based surface coatings in nuclear fuel element: I. selection, preparation, and characteristics of coating materials. Coatings, 10(9), 808.

66. Cheng, L.Y., Cuadra, A., Brown, N., 2014. PWR Plant Model to Assess Performance of Accident Tolerant Fuel in Anticipated Transients and Accidents. Brookhaven National Laboratory BNL-107113-2015-CP, Upton.

67. Nuclear Energy Institute, 2012. Diverse and Flexible Coping Strategies (FLEX) Implementation Guide, NEI 12-06 [Draft Rev. 0], dated August 2012. OECD NEA, 2018. State-of-the-Art Report on Light Water Reactor Accident-Tolerant Fuels. NEA No. 7317.

68. Special Reference: Nuclear Energy Agency, State-of-the-Art Report on Light Water Reactor Accident-Tolerant Fuel. NEA No.7317, OECD, 2018.

69. Shirvan K., 2019. Development of Accident Tolerant Fuel Options for Near Term Applications, Integrated University Project Final Report, NEUP No. 15-8843. Solis, J., Ivanov, K. and Sarikaya, B., 2001. Boiling Water Reactor Turbine Trip (TT) Benchmark, Volume 1: Final Specifications. NEA/NSC/DOC (2001)1.

70. Shah, H., Romero, J., Xu, P., Maier, B., Johnson, G., Walters, J., Dabney, T., Yeom, H., Sridharan, K., 2017. Development of surface coatings for enhanced accident tolerant fuel (atf). In: 2017 WRFPM – Water Reactor Fuel Performance Meeting, Jeju, Korea.
71. George, N.M., Terrani, K.A., Powers, J.J., 2013. Neutronic analysis of candidate accident-tolerant iron alloy cladding concepts. ORNL/TM-2013 121.
72. Rearden, B.T., Jessee, M., 2016. SCALE Code System. ORNL/TM-2005/39. Schanz, G., 2003. Recommendations and supporting information on the choice of zirconium oxidation models in severe accident codes, vol. 6827. FZKA.
73. Krausova, A., Tuma, L., Novak, M., Cvrcek, L., Krejci, J., Macak, J., 2017. Chromium coating as a surface protection of zirconium alloys. Koroze a ochrana materialu 61.
74. Baris, A., Abolhassani, S., Chiu, Y. L., & Evans, H. E. (2018). Observation of crack microstructure in oxides and its correlation to oxidation and hydrogen-uptake by 3D FIB Tomography–case of Zr-ZrO2 in reactor. Materials at High Temperatures, 35(1-3), 14-21.
75. M.T.S. Systems, Corporation Technical Staff, User Manua Nano Indenter G200, MTS Systems Corporation, 2007.
76. Yagnik, S. K., Hermann, A., & Kuo, R. C. (2005, January). Ductility of Zircaloy-4 fuel cladding and guide tubes at high fluences. In Zirconium in the Nuclear Industry: Fourteenth International Symposium. ASTM International.
77. Nechak, L., Berger, S., & Aubry, E. (2011). A polynomial chaos approach to the robust analysis of the dynamic behaviour of friction systems. European Journal of Mechanics-A/Solids, 30(4), 594-607.
78. Gispert, M. P., Serro, A. P., Colaco, R., & Saramago, B. (2006). Friction and wear mechanisms in hip prosthesis: Comparison of joint materials behaviour in several lubricants. Wear, 260(1-2), 149-158.

79. Yilmazbayhan, A., Motta, A. T., Comstock, R. J., Sabol, G. P., Lai, B., & Cai, Z. (2004). Structure of zirconium alloy oxides formed in pure water studied with

synchrotron radiation and optical microscopy: relation to corrosion rate. Journal of Nuclear Materials, 324(1), 6-22.

80. Dong, H., & Bell, T. (2000). Enhanced wear resistance of titanium surfaces by a new thermal oxidation treatment. Wear, 238(2), 131-137.
81. Roco, M. C., Mirkin, C. A., & Hersam, M. C. (2011). Nanotechnology research directions for societal needs in 2020: retrospective and outlook (Vol. 1). Springer Science & Business Media.
82. Krawiec, H., Vignal, V., Krystianiak, A., Gaillard, Y., & Zimowski, S. (2019). Mechanical properties and corrosion behaviour after scratch and tribological tests of electrodeposited Co-Mo/TiO2 nano-composite coatings. Applied Surface Science, 475, 162-174.
83. Cockeram, B. V., Leonard, K. J., Byun, T. S., Snead, L. L., & Hollenbeck, J. L. (2014). Development of microstructure and irradiation hardening of Zircaloy during low dose neutron irradiation at nominally 377–440° C. Journal of Nuclear Materials, 449(1-3), 69-87.
84. Arabi, M., Madani, S. M., & Mahmodi, S. (2019). Investigation of the Physical and Mechanical Properties of Silicon Carbide Prepared on an Industrial Scale. Advanced Ceramics Progress, 5(4), 1-6.
85. Fan, J., & Chu, P. K. (2014). Silicon carbide nanostructures: fabrication, structure, and properties. Springer.
86. Lodhe, M., Chawake, N., Yadav, D., & Balasubramanian, M. (2016). On correlation between β→ α transformation and densification mechanisms in SiC during spark plasma sintering. Scripta Materialia, 115, 137-140.
87. Federal Law "On the Fundamentals of Labor Protection in the Russian Federation" of 17.07.99 № 181 – FZ.
88. SanPiN 2.2.2 / 2.4.1340-03. Sanitary-epidemiological rules and standards "Hygienic requirements for PC and work organization".
89. GOST 12.1.038-82 Occupational safety standards system. Electrical safety.
90. Fire and explosion safety of industrial facilities. GOST R12.1.004-85 Occupational safety standards system. Fire safety.