RESEARCH PROPOSAL

CAVITATION EROSION OF BLENDED STELLITE ALLOYS

by

Vishakh Pradeep Kumar

Submitted for the degree of
MSc. Mechanical Engineering

School of Engineering and Physical Sciences
Heriot-Watt University

April 2024

Abstract

Cavitation erosion is a complex phenomenon influenced by the intensity of cavitating bubbles and material resistance, leading to performance degradation through material loss. This research endeavors to evaluate the resistance of blended stellite alloys to cavitation erosion. The study will investigate the synergy between cavitation and corrosion through in-situ electrochemical measurements. Experimental procedures will involve an ultrasonic vibratory horn operating at a fixed frequency of 20 kHz, with adjustable peak-to-peak amplitude. Microstructural characterization of cavitated sample surfaces and underlying cross-sections affected by cavitation will be conducted using scanning electron microscopy.

Contents

Chapter 1

Introduction

Cavitation erosion occurs when vapor bubbles form and collapse within a fluid due to local pressure reaching the vapor pressure threshold [1–3]. The implosion emits heat [4], shockwaves [5], and microjets [6] that damage adjacent solid surfaces, leading to material removal due to cumulative cavitation events [7, 8]. The resulting stress levels, as seen in Figure 1, can exceed material thresholds, causing surface damage and system degradation [9]. Understanding material response to cavitation stresses is crucial for selecting resistant materials and minimizing maintenance costs.

Stellites are cobalt-chromium alloys that are typically used for surfaces in lubrication-starved, high temperature or corrosive environments [10–14], such as in the nuclear industry [15–17], oil & gas [18, 19], marine [20], power generation [21], and aerospace industries [22]. The wear resistance of different stellite alloys manufactured by casting, forging, laser cladding, and hot isostatic pressing (HIP) has been investigated extensively, [12, 13, 23–31]. The cavitation erosion of stellites has been investigated in experimental studies [21, 32–50], along with investigations into cobalt-based alloys [51–61].

Ahmed et al. have investigated the impact of HIP'ing on stellite alloys, finding superior impact and fatigue resistance compared to cast stellite alloys [62–67]. They also explored blended alloys formed by consolidating two stellite powders, resulting in unique microstructures influenced by the different diffusion rates of added

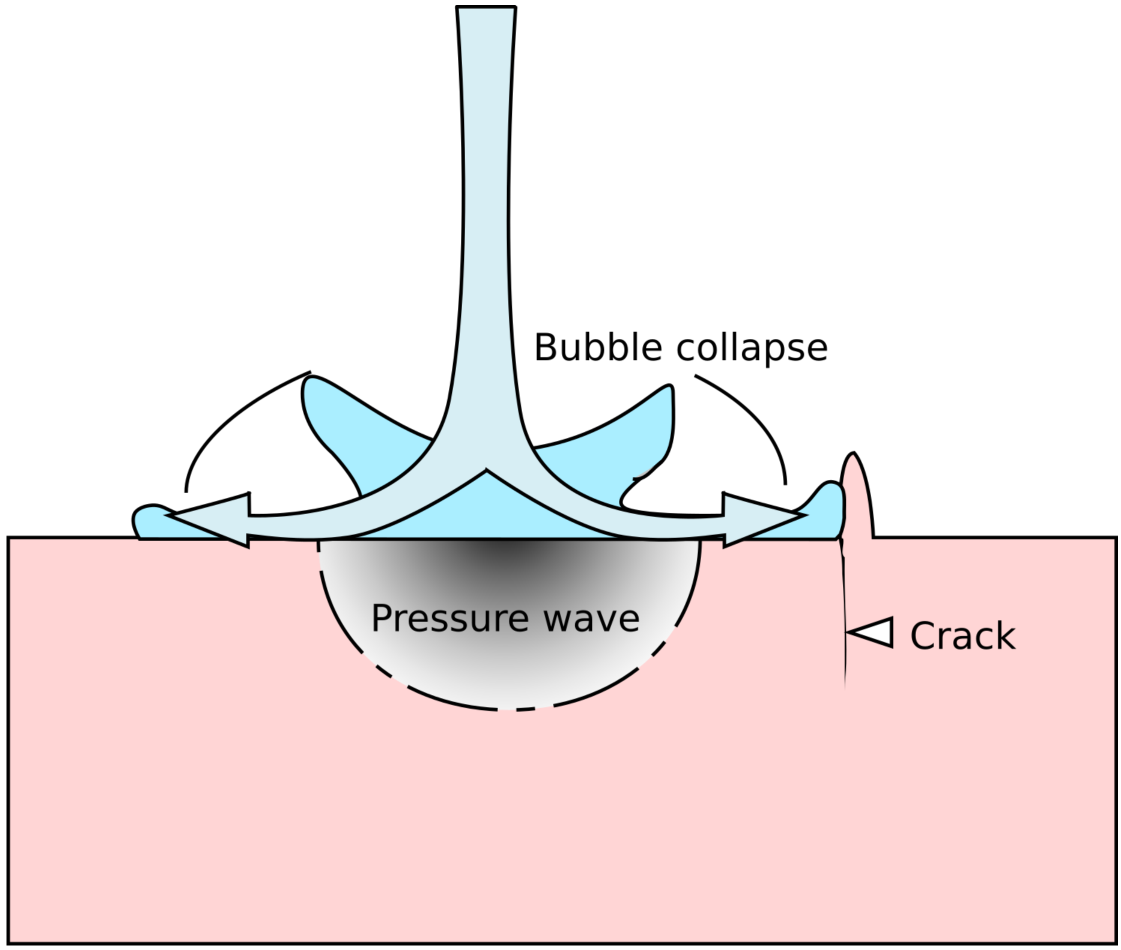


Figure 1.1: Damage mechanism of cavitation

elements. Depending on the composition of the stellite powders used, the blended alloys possess uniform microstructure or regions that are similar to the constituent powders [11, 62]. This is due to the different diffusion rates of the added elements - carbon diffuses through the blended alloys while tungsten cannot diffuse due to its high atomic radius [11, 62].

In light of the advantageous impact of fine carbide structure and microstructure on cavitation erosion, the lack of academic investigation into cavitation erosion on HIP'ed stellite alloys highlights the imperative for additional research. Investigating the effects of alloy composition & microstructure of blended alloys on their cavitation erosion behaviour promises to yield deeper insights into stellite performance under such conditions.

1.1 Aims and Objectives

Cavitation erosion impacts various industrial components, lowering their service life and increasing overall costs. In order to minimize damage & losses due to cavitation, the mechanisms by which materials degrade under cavitation erosion need to be understood. This work aims at identifying the most relevant factors to the cavitation erosion of base and blended stellite alloys, with a focus on how composition and microstructure affect cavitation resistance. The objectives of this work are to:

1. **Design and develop** an experimental rig capable of accurately simulating cavitation erosion conditions in distilled water & artificial seawater and achieving measurable & replicable erosion rates, **by end of May**.
2. **Quantify** cavitation erosion resistance of stellite materials in distilled water and artificial seawater **by end of June**.
3. **Investigate** the morphology, microstructure, chemical composition, and surface characteristics of eroded stellite samples **by end of July**.
    (a) **Acquire** Optical Microscopy images of eroded stellite samples at different stages of testing, in order to track changes of overall morphology of eroded surface.
    (b) **Acquire** Scanning Electron Microscopy (SEM) images of eroded stellite samples to analyze the microstructural changes and phase composition resulting from cavitation erosion.
    (c) **Acquire** Energy Dispersive X-ray Spectrometry (EDS) images and scans to analyze the elemental composition of specific regions on the eroded stellite samples (elemental composition of matrix, carbides, and interfaces)
4. **Develop** mathematical models for cavitation erosion of stellite alloys **by end of July**.
    (a) **Investigate** the relationship between composition and previously reported structure-property relationships to cavitation erosion rates.

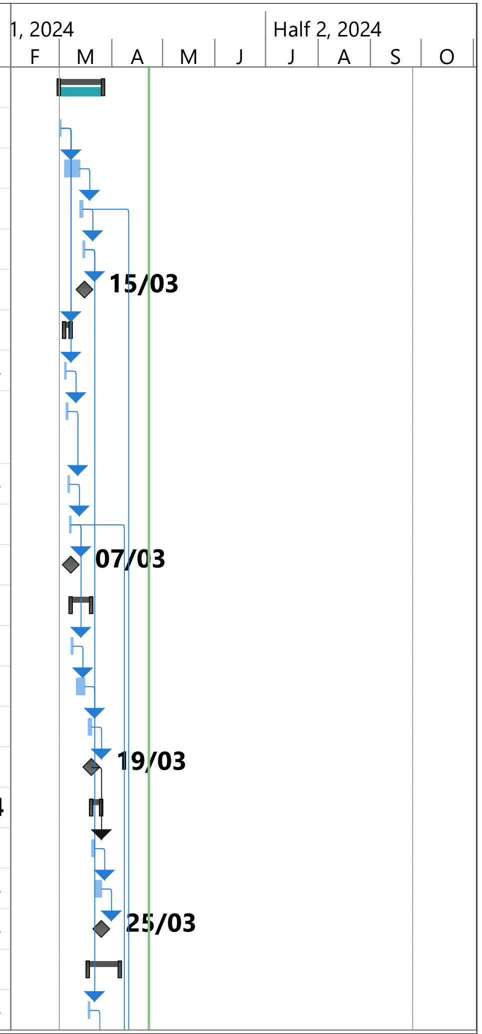
   (b) **Assess** the applicability of parameter-models of cavitation erosion to experimental data of the cumulative mass loss of stellites.

5. **Understand** the cavitation mechanism in stellite alloys and describe a phenomological model of CE in stellite alloys and provide actionable recommendations for enhancing cavitation resistance in stellite alloys

Finite element simulations (FEA) and other numerical simulation techniques are outside the the scope of this thesis.

1.2 Gantt Chart

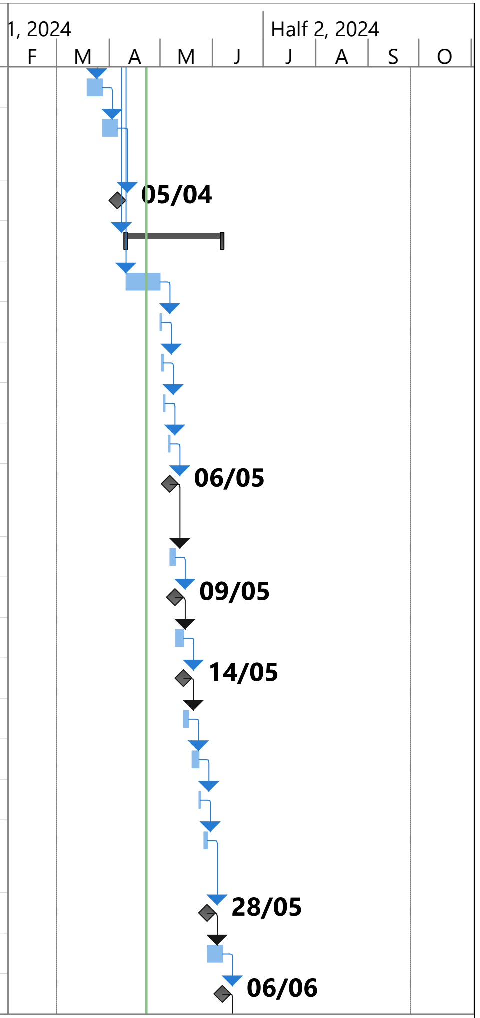
ID		Task Mode	Task Name	Duration	Start	Finish
1			**1 Project Planning and Preparation**	**18 days**	**Fri 01/03/24**	**Tue 26/03/24**
2			1.1 Define research objectives and scope	1 day	Fri 01/03/24	Fri 01/03/24
3			1.2 Conduct literature review on cavitation erosion a	7 days	Mon 04/03/24	Tue 12/03/24
4			1.3 Develop research methodology	2 days	Wed 13/03/24	Thu 14/03/24
5			1.4 Obtain feedback	1 day	Fri 15/03/24	Fri 15/03/24
6			1.5 Deliverable - Aims & Objectives	0 days	Fri 15/03/24	Fri 15/03/24
7			**1.6 Resource Management**	**4 days**	**Mon 04/03/24**	**Thu 07/03/24**
8			1.6.1 Define Resource Requirements	1 day	Mon 04/03/24	Mon 04/03/24
9			1.6.2 Identification of types of resources needed (e.g., personnel, equipment, materials)	1 day	Tue 05/03/24	Tue 05/03/24
10			1.6.3 Resource - Personnel	1 day	Wed 06/03/24	Wed 06/03/24
11			1.6.4 Resource - Equipment	1 day	Thu 07/03/24	Thu 07/03/24
12			1.6.5 Deliverable - Resource Management	0 days	Thu 07/03/24	Thu 07/03/24
13			**1.7 Risk Management**	**8 days**	**Fri 08/03/24**	**Tue 19/03/24**
14			1.7.1 Identification of risks	1 day	Fri 08/03/24	Fri 08/03/24
15			1.7.2 Identification of Likelihood and Impact of Ide	5 days	Mon 11/03/24	Fri 15/03/24
16			1.7.3 Identify Risk Mitigation Strategies	2 days	Mon 18/03/24	Tue 19/03/24
17			1.7.4 Deliverable - Risk Management	0 days	Tue 19/03/24	Tue 19/03/24
18			**1.8 Beneficiaries & Stakeholder**	**4 days**	**Wed 20/03/24**	**Mon 25/03/24**
19			1.8.1 Identification of beneficiaries	2 days	Wed 20/03/24	Thu 21/03/24
20			1.8.2 Identification of stakeholders	2 days	Fri 22/03/24	Mon 25/03/24
21			1.8.3 Deliverable - Beneficiaries & Stakeholder	0 days	Mon 25/03/24	Mon 25/03/24
22			**2 Material Preparation**	**15 days**	**Mon 18/03/24**	**Fri 05/04/24**
23			2.1 Procure Stellite samples of different composition	1 day	Mon 18/03/24	Mon 18/03/24



Project: WBS
Date: Tue 23/04/24

Task
Split
Milestone
Summary
Project Summary
Inactive Task
Inactive Milestone
Inactive Summary
Manual Task
Duration-only
Manual Summary Rollup
Manual Summary
Start-only
Finish-only
External Tasks
External Milestone
Deadline
Progress
Manual Progress

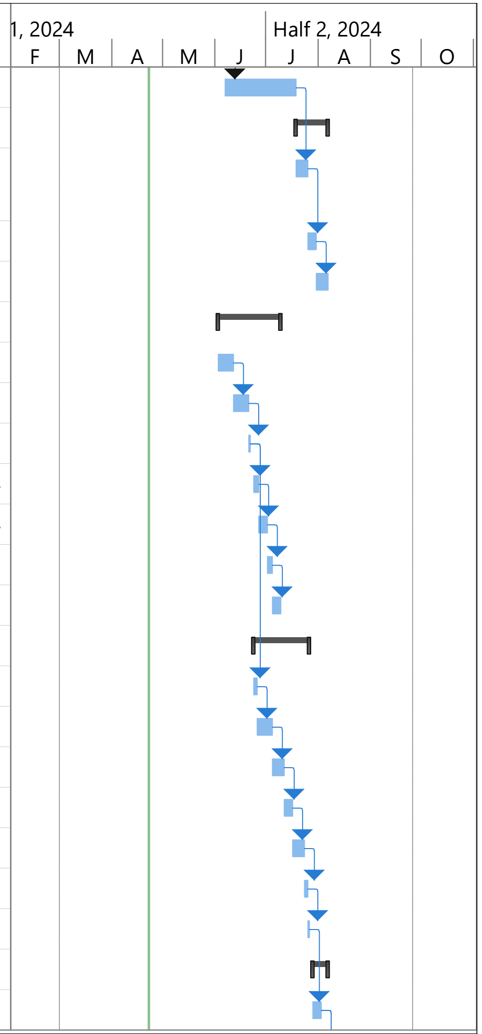
ID	Task Mode	Task Name	Duration	Start	Finish
24		2.2 Prepare Stellite samples for testing (e.g., cutting,	7 days	Tue 19/03/24	Wed 27/03/24
25		2.3 Characterize Stellite samples (images, density measurement, marking, inventory management)	7 days	Thu 28/03/24	Fri 05/04/24
26		2.4 Milestone - Sample handover	0 days	Fri 05/04/24	Fri 05/04/24
27		**3 Experimental Rig Setup**	**41 days**	**Thu 11/04/24**	**Thu 06/06/24**
28		3.1 Design cavitation erosion test rig	14 days	Thu 11/04/24	Tue 30/04/24
29		3.2 Review cavitation erosion design - Ahmed Algobu	1 day	Wed 01/05/24	Wed 01/05/24
30		3.3 Review cavitation erosion design - Dr Rehan Ahm	1 day	Thu 02/05/24	Thu 02/05/24
31		3.4 Review cavitation erosion design - Dr Mohamme	1 day	Fri 03/05/24	Fri 03/05/24
32		3.5 Review cavitation erosion design - Muhsin Aykap	1 day	Mon 06/05/24	Mon 06/05/24
33		3.6 Milestone - Acquire equipment for cavitation erosion rig	0 days	Mon 06/05/24	Mon 06/05/24
34		3.7 Structure Assembly	3 days	Tue 07/05/24	Thu 09/05/24
35		3.8 Milestone - Assemble Design	0 days	Thu 09/05/24	Thu 09/05/24
36		3.9 Mounting of Equipment	3 days	Fri 10/05/24	Tue 14/05/24
37		3.10 Milestone - Equipment Mounted	0 days	Tue 14/05/24	Tue 14/05/24
38		3.11 Wiring of Power Cables	3 days	Wed 15/05/24	Fri 17/05/24
39		3.12 Wiring of Signal Cables	4 days	Mon 20/05/24	Thu 23/05/24
40		3.13 Connection of Fluid Cables	1 day	Fri 24/05/24	Fri 24/05/24
41		3.14 Calibrate instrumentation (e.g., ultrasonic transducers, pressure sensors)	2 days	Mon 27/05/24	Tue 28/05/24
42		3.15 Milestone - Equipment Components functional	0 days	Tue 28/05/24	Tue 28/05/24
43		3.16 Integration Testing	7 days	Wed 29/05/24	Thu 06/06/24
44		3.17 Milestone - Stainless steel samples	0 days	Thu 06/06/24	Thu 06/06/24



Project: WBS
Date: Tue 23/04/24

Task		Inactive Summary		External Tasks	
Split		Manual Task		External Milestone	
Milestone		Duration-only		Deadline	
Summary		Manual Summary Rollup		Progress	
Project Summary		Manual Summary		Manual Progress	
Inactive Task		Start-only			
Inactive Milestone		Finish-only			

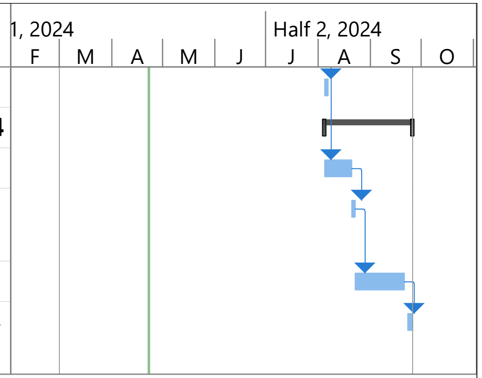
ID		Task Mode	Task Name	Duration	Start	Finish
45			4 Cavitation Testing	30 days	Fri 07/06/24	Thu 18/07/24
46			**5 Data Analysis**	**13 days**	**Fri 19/07/24**	**Tue 06/08/24**
47			5.1 Process experimental data (e.g., erosion depth measurements, surface roughness data)	5 days	Fri 19/07/24	Thu 25/07/24
48			5.2 Fit to parameter models	3 days	Fri 26/07/24	Tue 30/07/24
49			5.3 Analyze cavitation erosion mechanisms and patte	5 days	Wed 31/07/24	Tue 06/08/24
50			**6 Material characterization**	**27 days**	**Mon 03/06/24**	**Tue 09/07/24**
51			6.1 EDM Wire Cutting	7 days	Mon 03/06/24	Tue 11/06/24
52			6.2 Sample Preparation	7 days	Wed 12/06/24	Thu 20/06/24
53			6.3 Resin Casting	1 day	Fri 21/06/24	Fri 21/06/24
54			6.4 SEM & EDS - Visit 1	3 days	Mon 24/06/24	Wed 26/06/24
55			6.5 SEM & EDS - Visit 2	3 days	Thu 27/06/24	Mon 01/07/24
56			6.6 SEM & EDS - Visit 3	3 days	Tue 02/07/24	Thu 04/07/24
57			6.7 SEM & EDS - Visit 4	3 days	Fri 05/07/24	Tue 09/07/24
58			**7 Reporting and Documentation**	**25 days**	**Mon 24/06/24**	**Fri 26/07/24**
59			7.1 Create visualizations (e.g., graphs, charts) to illust	2 days	Mon 24/06/24	Tue 25/06/24
60			7.2 Adapt Literature Review	7 days	Wed 26/06/24	Thu 04/07/24
61			7.3 Milestone - Report - Introduction	5 days	Fri 05/07/24	Thu 11/07/24
62			7.4 Milestone - Report - Methodology	3 days	Fri 12/07/24	Tue 16/07/24
63			7.5 Milestone - Report - Results & Discussion	5 days	Wed 17/07/24	Tue 23/07/24
64			7.6 Milestone - Report - Conclusion	2 days	Wed 24/07/24	Thu 25/07/24
65			7.7 Milestone - Report - Abstract	1 day	Fri 26/07/24	Fri 26/07/24
66			**8 Presentation**	**7 days**	**Mon 29/07/24**	**Tue 06/08/24**
67			8.1 Create presentation materials (e.g., slides)	5 days	Mon 29/07/24	Fri 02/08/24



Project: WBS
Date: Tue 23/04/24

Task		Inactive Summary		External Tasks	
Split		Manual Task		External Milestone	
Milestone		Duration-only		Deadline	
Summary		Manual Summary Rollup		Progress	
Project Summary		Manual Summary		Manual Progress	
Inactive Task		Start-only			
Inactive Milestone		Finish-only			

ID	ⓘ	Task Mode	Task Name	Duration	Start	Finish
68			8.2 Practice oral presentation	2 days	Mon 05/08/24	Tue 06/08/24
69			**9 Publication**	**38 days**	**Mon 05/08/24**	**Wed 25/09/24**
70			9.1 Write conference paper	12 days	Mon 05/08/24	Tue 20/08/24
71			9.2 Present research findings at conferences, seminars, or workshops	2 days	Wed 21/08/24	Thu 22/08/24
72			9.3 Write journal paper	21 days	Fri 23/08/24	Fri 20/09/24
73			9.4 Publish research findings in scientific journals or other relevant publications	3 days	Mon 23/09/24	Wed 25/09/24



Project: WBS
Date: Tue 23/04/24

Task	Inactive Summary	External Tasks
Split	Manual Task	External Milestone
Milestone	Duration-only	Deadline
Summary	Manual Summary Rollup	Progress
Project Summary	Manual Summary	Manual Progress
Inactive Task	Start-only	
Inactive Milestone	Finish-only	

1.3 Resources

The designed rig will require the use of the following equipment

- Q500 Sonicator (existing)
- Vacuum Pump and Dessicator (purchased)
- Chilled Water Supply (existing)
- Coiled heat exchanger (purchased)
- Air Compressor (existing)

This work will require access to the following Heriot-Watt University laboratories.

- Energy Laboratory

  Location of relevant existing equipment (sonotrode, microscope, precision balance). There are two computers in the Energy Lab, the first to control the microscope and to handle image processing through ImageJ, and second for general purpose computing. The second computer has an automated backup, in addition to version control on all data stored.
- Chemical Laboratory

  Acetone is stored in Flammable Liquid Storage Cabinet in Chemical Lab, with purchase of more acetone available through vendors registered with Procurement. Distilled water is provided by Type 1 water purification system in the Chemical Laboratory.
- Fabrication & Automotive Laboratory

  Access to tools for modification of equipment.
- Electronics Laboratory

  Access to soldering equipment for work on unpowered equipment.

In addition to the above, the following items are required:

- Specimens of Blended Stellite Alloys (provided by Dr Rehan Ahmed)
- Access to material characterization equipment (SEM, EDS, and XRD) through MoU w/ University of Sharjah.

1.4 Risks

The major obstacle for this project is the potential for time constraints and delays, especially those that were not adequately accounted for during the initial project planning phase.

1.4.1 Experimental setup complexity risks

Experimental setup could pose unexpected issues due to lack of planning. In order to mitigate the risk of unexpected design changes, the following strategies are to be employed:

- Detailed Planning and Design in CAD

  The rig is to be designed in CAD to ensure all subsystems meet spatial, power, and I/O requirements.
- Expert Consultation & Review

  The rig design is to be reviewed by supervisor and other expereinced researchers & engineers. Feedback is to be recorded and designed altered to alleviate concerns. Identified people for review are Dr Rehan Ahmed, Dr Mohammed Al-Musleh, Muhsin Aykapaddatu
- Functionality/performance is not as expected or to specification

  Pilot testing of the rig to ASTM G32 standards using known materials (e.g., 316L stainless steel) will verify functionality and performance, comparing results with existing data.
- Documenting Procedures and Troubleshooting Protocols

  Detailed documentation of components and development of a Standard Operating Procedure (SOP) aligned with ASTM G32 standards will be maintained. Troubleshooting protocols will be established for unforeseen issues.
- Modular Design & Redundancies

  The rig will feature a modular design for easy component adjustment. Spare parts will be readily available for quick replacement or repair, minimizing downtime.

1.4.2 Health & Safety risks

The primary H&S risks are Noise Exposure and Chemical Hazards (exposure to acetone). Both of these risks have been investigated in existing risk assessments for equipment have been attached to the appendix for the reader's perusal. Unlike the proposed additions, these equipment involve human interaction, requiring the need for a more comprehensive risk assessment. The risk assessments were written by the author, with feedback from project supervisor and lab manager.

- Grinder-Polisher, available at Appendix A.1
- Ultrasonic Bath, available at Appendix A.2
- Cavitation Equipment, available at Appendix A.3

1.5 Beneficiaries & Stakeholders

Industrial manufacturers and technology providers will benefit from improved understanding of cavitation erosion in stellite alloys, enabling the development of more durable materials for applications in harsh environments, such as hydroelectric power plants [47], Francis turbines [68], nuclear power plant valves [17, 69], condensate and boiler feedwater pumps [70], marine propellers [71], liquid-lubricated journal bearings [72], pipline reducers [73–75].

The project supervisor and academic faculty represent the primary stakeholders, whose critique will be necessary for attaining project & academic objectives. Apart from serving as mentor, the project supervisor has provided rare specimens and leveraged inter-university connections to access material characterization facilities, enhancing the project's resources and capabilities. Other stakeholders are:

- Peer Researchers: offer peer review and collaboration, in addition to being users of similar equipment. Undergraduate students are unlikely to be present during project duration, although they are likely to be end users of equipment after project close.
- Research Community: contribute to understanding of cavitation erosion and

benefit from data. Project outcomes generate data and contribute to understanding of cavitation erosion.

- Lab Management: ensure compliance with health and safety requirements. Additionally, the lab management consists of doctoral students working on other research equipment; their advice will helpful when troubleshooting issues that arise.

Chapter 2

Literature Review

Cavitation erosion is a complex phenomenon that results from hydrodynamic elements and material characteristics [7], resulting in degraded component surfaces and material erosion.

From a hydrodynamic standpoint, cavitation erosion results from the formation of and subsequent collapse of vapor bubbles within a fluid medium, due to the local pressure reaching the saturated vapor pressure, either due to pressure decrease (cavitation) or temperature increase (boiling). When these bubbles implode, they emit heat, shockwaves, and high-speed microjets that can impact adjacent solid surfaces, leading to damage to the surface and removal of material due to the accumulation of damage following numerous cavitation events [76–78]. The required pressure drop required by cavitation could be provided by the propagation of ultrasonic acoustic waves and hydrodynamic pressure drops, such as constrictions or the rotational dynamics of turbomachinery [79]. Impurities in the fluid, such as solid particles and nanobubbles can significantly reduce the cavitation threshold leading to increased cavitation intensity [80]. When these bubbles collapse near walls, the concentration of energy on very small areas of the wall result in high stress levels [81].

The resultant stress levels, which range from 100 - 1000 MPa, can surpass material resistance thresholds, including yield strength, ultimate strength, or fatigue limit, leading to material removal from the surface and subsequent degradation of industrial systems [76–78]. The high strain rate in cavitation erosion makes it rather comparable to explosions or projectile impacts, albeit with very limited volume of deformation and repeated impact loads [82–87]. The plastic deformation results in progressive hardening, crack propagation, local fracture and loss of material, with the overall damage being a function of intensity and frequency of vapor bubble collapse [88–90]. The selection of more resistent materials requires investigation of material response to cavitation stresses, with the mechanism of erosion being of particular interest [91–93]. The resulting reduction of performance & service life and the increased maintenance and repair costs motivate research into understanding how materials respond to the impact of a cavitating material.

2.1 Measuring cavitation erosion through ASTM G32

The ASTM G32 standard defines the study of cavitation performance of materials by placing an ultrasonic sonotrode above a stationary specimen, forming a thin liquid layer between the two solid walls, as seen in Figure 2.1. The sonotrode horn emits an acoustic wave into the fluid and causes cavitation when the pressure amplitude is sufficiently high. Due to the reflection and superposition of ultrasound in the thin liquid layer, the intensity of cavitating bubbles is increased, leading to accelerated cavitation erosion [80, 94, 95].

2.1.1 Effect of distance between sonotrode and specimen

Endo et al [96] found that the extent of damage depends upon the thickness of the thin liquid layer, Kikuchi et al [97] find that the extent of damage is a function of the reciprocal of the thickness of the liquid layer. For thicknesses $h < 0.5mm$, numerous bubbles coalese into several large bubble clusters in contact with the horn tip and the staionary specimen, while for thicknesses $h > 0.5mm$, the numerous bubbles produced are isolated [98–100].

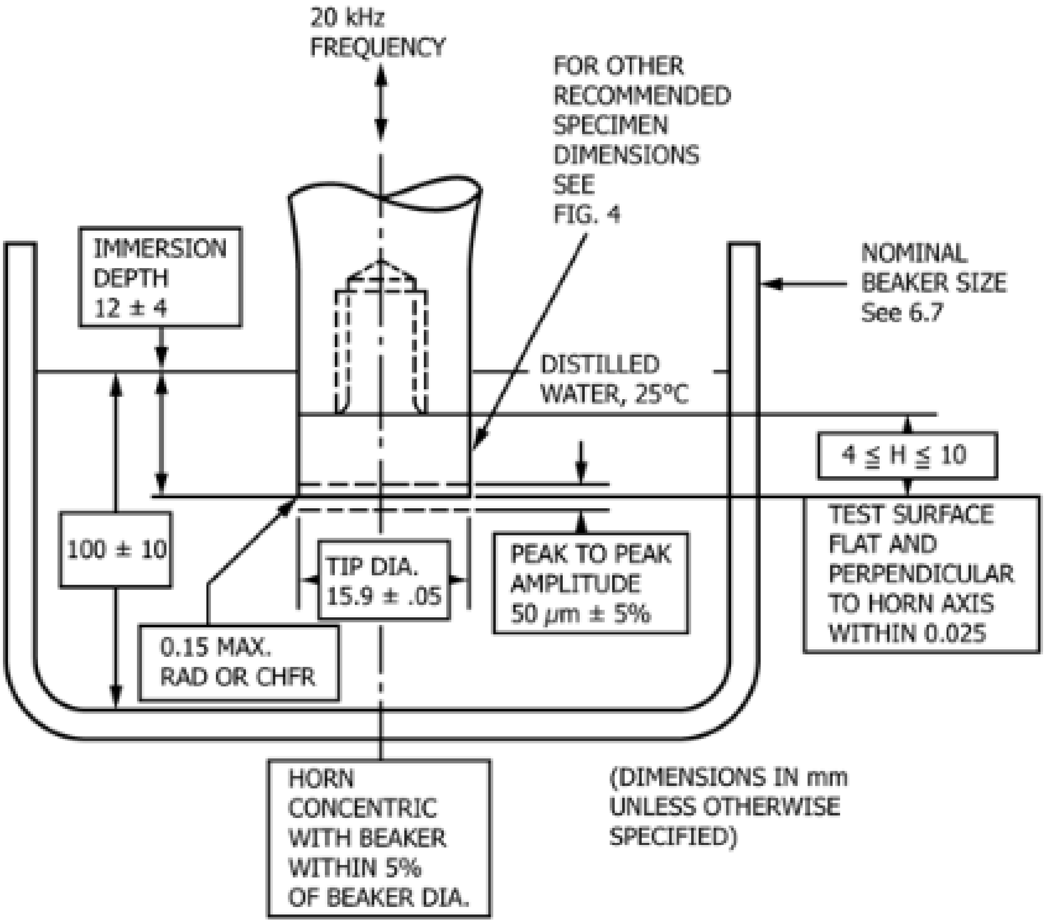


Figure 2.1: Important parameters of experimental apparatus from ASTM G32. From [94]

2.1.2 Effect of liquid temperature

The test water temperature affects the degree of cavitation erosion [101, 102], with mass loss rate initially increasing with increase in temperature, peaking at an optimum temperature T_m, then decreasing with further increase in temperature [103], with bulk liquid temperatures above 50 C not altering erosion rate significantly [101, 104]. However, it must be noted that the temperature of the liquid film between the ultrasonic tip and sample rises rapidly, regardless of the bulk liquid temperature [96, 99], with maximum erosion rates observed with film temperatures at temperatures 30-35 C [101, 105].

2.2 Stellite

Stellite alloys belong to the cobalt-chromium family, with the addition of tungsten or molybdenum as the main alloying elements. The matrix in stellite alloys consist of cobalt (Co) with solid-solution strengthening of a substantial amount of chromium (Cr) and tungsten(W)/moblybdenum(Mo), resulting in high hardness & strength at high temperature, with carbide precipitations (Co, Cr, W, and/or Mo carbides) adding strength and wear resistance [26, 27, 62, 106–108]. Stellites are typically used for wear-resistant surfaces in lubrication-starved, high temperature or corrosive environments [10–14], such as in the nuclear industry [15–17], oil & gas [18, 19], marine [20], power generation [21], and aerospace industries [22].

The wear resistance of different stellite alloys manufactured by casting, forging, laser cladding, and hot isostatic pressing (HIP) has been investigated extensively, [12, 13, 23–31]. Hot Isostatic Pressing (HIP) consolidation of Stellite alloys offers significant technological advantages for components operating in aggressive wear environments [12, 22, 64, 66]. Yu et al [30, 67] note that HIP consolidation results in superior impact and fatigue resistance over cast alloys. The cavitation erosion of stellites has been investigated in experimental studies, as seen in Table 2.1, [21, 32–50], along with investigations into cobalt-based alloys [51–61], though the cavitation erosion mechanism has not been fully established, particularly the effect of microstructure due to different fabrication techniques, as seen in Figure 2.2. In addition to the energy absorbing effect of phase transformation of the cobalt matrix [61], Heathcock et al [109] find that finer carbide structure leads to increased cavitation erosion resistance, an observation ratified by Garzon et al [110]. Cavitation erosion of stellite coatings is improved in seawater, when compared to distilled water [52], likely due to the protective effect of chromium oxides inhibiting formation of erosion pits [53].

Corrosion studies conducted on stellites find high corrosion resistance due to the substantial percentage of Cr in the matrix. The matrix is preferentially attacked, with the dissolution of Co into Co^{2+}, while a surface layer comprised of chromium-rich oxides (Cr_2O_3 & $Cr(OH)_3$) prevents further corrosion in chloride-rich environments.

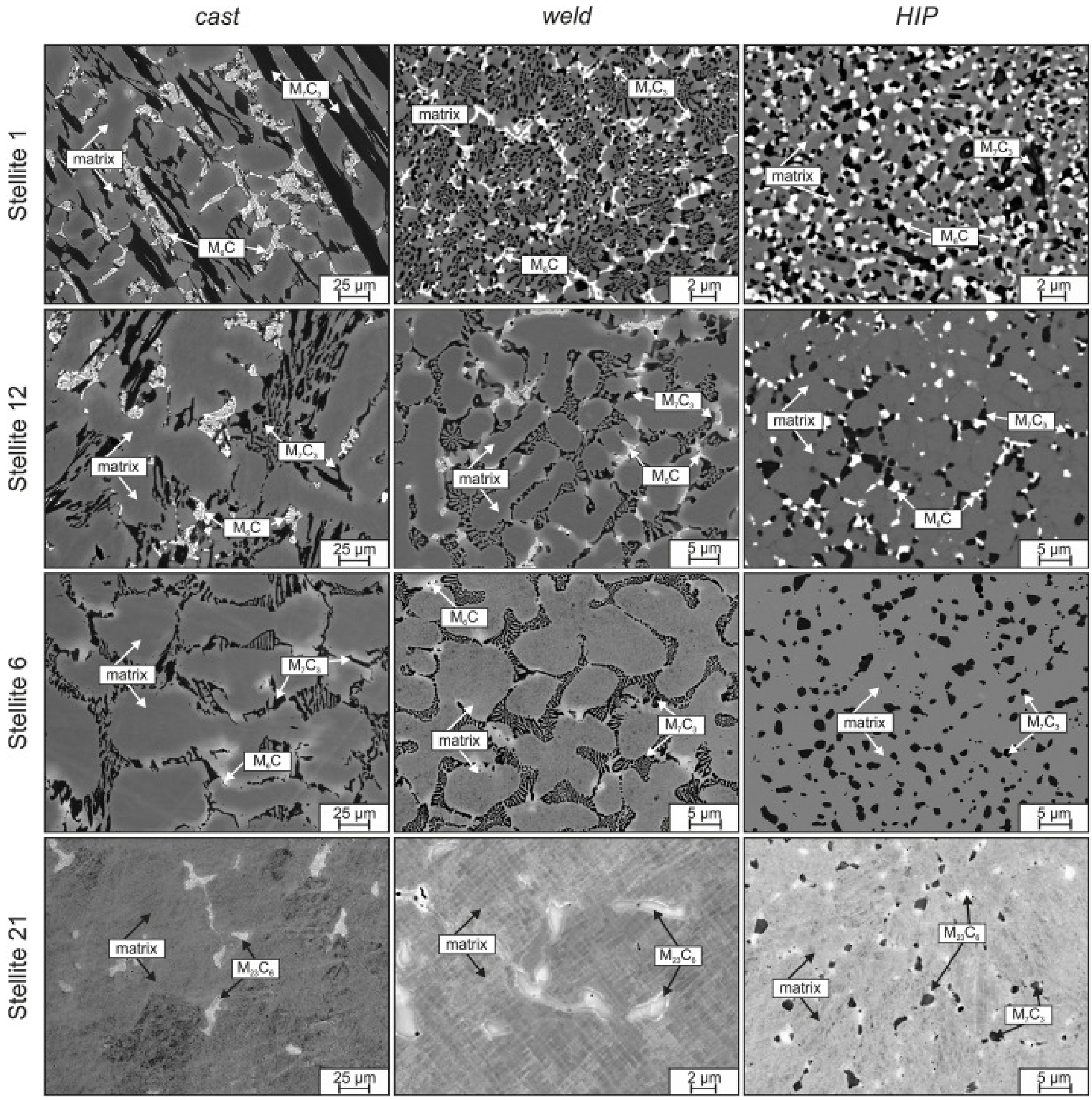


Figure 2.2: Microstructure of Stellite alloys 1, 12, 6, & 21 due to casting, welding, and HIP'ing. From [31].

Zhang et al find that stellite alloys with higher carbon content have less corrosion resistance [10]. Malayoglu et al find improved erosion and corrosion resistance of HIP'ed Stellite 6 over cast Stellite 6, due to lessened removal of Co-rich matrix in HIP'ed material. [111]. Mohamed et al report similar improved performance of HIP'ed Stellite 6 and attribute it to the fine grain size of carbides in HIP'ed materials [112].

2.2.1 Matrix phase

Cobalt and Co-Cr alloys undergo thermally induced phase transformation from the high temperature face-centered cubic (FCC) γ phase to low temperature hexag-

Table 2.1: Operating parameters used in ASTM G32 tests on Stellite specimens

Test method	Medium	Material	Peak to Peak Amplitude (µm)	Water Temperature (°C)	Standoff Distance (mm)	Test Duration (hr)	Total Duration (hr)	Terminal Erosion Rate for Eroded Area 199 mm^2 (mg h^{-1})	References
Indirect	Water	HIP'ed Stellite 6	50	-	0.5	1.5	24	2.09	[33]
Indirect	Water	$5 \times 10^{16} \frac{Mn^+}{cm^2}$ HIP'ed Stellite 6	50	-	0.5	1.5	24	2.07	[33]
Indirect	Water	$10 \times 10^{16} \frac{Mn^+}{cm^2}$ HIP'ed Stellite 6	50	-	0.5	1.5	24	1.88	[33]
Direct	Water	LC Stellite 6	50	25	-	1	14	2.7	[36]
Direct	Water	SLD Stellite 6	50	25	-	1	14	0.77	[36]
Direct	Water	HVOF Stellite 21	25	25	-	0.5	8	-	[35]
Direct	3.5 wt% NaCl	Stellite 728	50	25	-	5	50	1.012	[32]
Direct	3.5 wt% NaCl	Stellite 6	50	25	-	5	50	2.841	[32]
Direct	3.5 wt% NaCl	Stellite 6B	50	25	-	5	50	2.018	[32]
Direct	3.5 wt% NaCl	HVOF Stellite 21	25	25	-	0.5	8	-	[35]
Direct	3.5 wt% NaCl	LC Stellite 6	50	25	-	1	14	0.044	[38]
Direct	3.5 wt% NaCl	SLD-1.0kW Stellite 6	50	25	-	1	14	0.017	[38]
Direct	3.5 wt% NaCl	SLD-1.0kW Stellite 6	50	25	-	1	14	0.017	[38]

onal close-packed (HCP) ϵ phase at 700 K and strain induced FCC-HCP transition through martensitic-type mechanism (partial movement of dislocations) [32, 113]. At ambient conditions, the metastable FCC retained phase in stellites can be transformed into HCP phase by mechanical loading, although any HCP phase is completely transformed into a FCC phase between 673 K and 743 K [35, 114]; the metastable FCC cobalt phase in stellite alloys [36, 115] absorbs a large part of imparted energy under the mechanical loading of cavitation erosion. The FCC to HCP transition is related to the very low stacking fault energy of the FCC structure (7 mJ/m2) [33, 116, 117].

Solid-solution strengthening leads to increase of the FCC cobalt matrix strength (due to distortion of the atomic lattice with the addition of elements of different atomic radii), and decrease of low stacking fault energy [116] due to the adjusted electronic structure of the metallic lattice. Dislocation motion in stellites is discouraged by solute atoms of Mo and W, due to the large atomic sizes. Given that dislocation cross slip is the main deformation mode in imperfect crystals at elevated temperature, as dislocation slip is a diffusion process that is enhanced at high temperature, this leads to high temperature stability [118]. In addition, nickel (Ni), iron (Fe), and carbon (C) stabilize the FCC structure of cobalt (a = 0.35 nm), while chromium (Cr) and tungsten (W), stabilize the HCP structure (a = 0.25 nm and c = 0.41 nm) [116, 119].

2.2.2 Carbide phase

The amount and types of carbides dispersed in the stellite matrix are primarily determined by the carbon content, with higher carbon content encouraging carbides with higher C/M ratios, while the size of carbides is determined by the cooling rate [27, 29]. Carbon content can be used to distinguish between different stellite alloys: high-carbon stellites designed for high wear resistance, abrasion, & severe galling, medium-carbon ($0.5 - 1.6\%wt$) stellites used for high temperature service, and low-carbon ($< 0.5\%wt$) stellites used primarily for corrosion resistance, cavitation, & sliding wear [37, 120]. Low-carbon stellites depend primarily on solid-solution strengthening for their mechanical properties. As the carbon content increases, the W/Mo content is usually also increased to prevent depletion of Cr from matrix solid solution strengthening [10, 112]. Chromium is the predominant carbide former, with M_7C_3 and $M_{23}C_6$ phases, in addition to providing corrosion resistance and strength to the stellite matrix [43–45]. Difference between the M_7C_3 and $M_{23}C_6$ phases is not readily visible under SEM. In tungsten-containing alloys, carbides of type M_7C_3 and M_6C are formed in addition to the matrix. Ahmed et al report on the identification of intermetallic Co_3W and Co_7W_6 phases through XRD, although these phases are not identified in SEM observations [31, 121, 122].

2.2.3 Blended Stellite Alloys

Ahmed et al investigate the influence of the HIP'ing process on stellites [62–67], and conclude that HIP consolidation of Stellite alloys offers significant technological advantages for components operating in aggressive wear environments due to superior impact and fatigue resistance over cast alloys [12, 22, 64, 66]. In order to achieve unique microstructures from existing stellite alloys, Ahmed et al investigate the performance of blended alloys [11, 62], which are formed through the consolidation of a mixture of two stellite powders.

A blended stellite alloy is formed by hot isostatic pressing of a mixture of two stellite powders. The powders are created through gas atomization, in which a stream of liquid stellite alloy is disrupted and atomized into tiny molten droplets by a high-pressure inert gas flow [11, 62, 123, 124]. The free-falling molten droplets rapidly solidify into spherical particles before being collected, forming high quality stellite powders with controllable size. The rapid cooling of the powder during atomization leads to reduced precipitation of carbides and supersaturation of the metallic matrix with other elements, as seen in the reduced proportion of carbide phases detected in the XRD performed on powders, compared to XRD of HIP'd samples. The mixing of powders is conducted in a powder hopper that ensures uniform distribution of powder mixtures [11, 62]. The HIP treatment was conducted at a temperature of 1200 C and a pressure of 100 MPa for a duration of 4 hours, resulting in full dense blended stellite alloys [125–127]. During the HIP'ing process, carbides are precipitated, in addition to reduction of supersaturation of the matrix [128, 129]. Depending on the composition of the stellite powders used, the blended alloys could possess uniform microstructure or regions that are similar to the constituent powders. This is due to the different diffusion rates of the added elements - carbon diffuses through the blended alloys while tungsten cannot diffuse due to its high atomic radius [11, 62, 130, 131].

In summary, this literature review emphasizes the necessity for additional academic inquiry into the cavitation erosion resistance of HIP'ed stellite alloys, with focus on the influence of composition on microstructure and cavitation erosion behavior. This thesis endeavors to address this gap in knowledge by conducting a comprehensive investigation.

Bibliography

[1] R.T. Knapp, J.W. Daily, and F.G. Hammitt. *Cavitation*. Engineering societies monographs. McGraw-Hill, 1970. URL: https://books.google.ae/books?id=T-hRAAAAMAAJ.

[2] C.E. Brennen. *Cavitation and Bubble Dynamics*. Oxford engineering science series. Oxford University Press, 1995. ISBN: 9780195094091. URL: https://books.google.ae/books?id=vYiUO0RlC4UC.

[3] W. Lauterborn and H. Bolle. "Experimental investigations of cavitation-bubble collapse in the neighbourhood of a solid boundary". In: *Journal of Fluid Mechanics* 72.2 (1975), pp. 391–399. DOI: 10.1017/S0022112075003448.

[4] Edward B. Flint and Kenneth S. Suslick. "The Temperature of Cavitation". In: *Science* 253.5026 (1991), pp. 1397–1399. DOI: 10.1126/science.253.5026.1397. eprint: https://www.science.org/doi/pdf/10.1126/science.253.5026.1397. URL: https://www.science.org/doi/abs/10.1126/science.253.5026.1397.

[5] Siyuan Geng et al. "Propagation of Shock Wave at the Cavitation Bubble Expansion Stage Induced by a Nanosecond Laser Pulse". In: *Journal of Fluids Engineering* 143.5 (Mar. 2021), p. 051209. ISSN: 0098-2202. DOI: 10.1115/1.4049933. URL: https://doi.org/10.1115/1.4049933.

[6] Jiupeng Xiong et al. "Quantitative evaluation of the microjet velocity and cavitation erosion on a copper plate produced by a spherical cavity focused transducer at the high hydrostatic pressure". In: *Ultrasonics Sonochemistry* 82 (2022), p. 105899. ISSN: 1350-4177. DOI: https://doi.org/10.1016/j.

ultsonch.2021.105899. URL: https://www.sciencedirect.com/science/article/pii/S1350417721004417.

[7] J.P. Franc and J.M. Michel. In: *Fundamentals of Cavitation* (2004). cited By 959, p. 265.

[8] A Karimi and JL Martin. "Cavitation erosion of materials". In: *International Metals Reviews* 31.1 (1986), pp. 1–26.

[9] F. Pereira, F. Avellan, and Ph. Dupont. "Prediction of Cavitation Erosion: An Energy Approach". In: *Journal of Fluids Engineering* 120.4 (Dec. 1998), pp. 719–727. ISSN: 0098-2202. DOI: 10.1115/1.2820729. URL: https://doi.org/10.1115/1.2820729.

[10] X.Z. Zhang et al. "Electrochemical Study of Corrosion Behavior of Wrought Stellite Alloys in Sodium Chloride and Green Death Solutions". In: *Journal of Materials Engineering and Performance* 24.9 (2015). Cited by: 6, pp. 3579–3587. DOI: 10.1007/s11665-015-1629-4.

[11] R. Ahmed, A. Fardan, and S. Davies. "Mapping the mechanical properties of cobalt-based stellite alloys manufactured via blending". In: *Advances in Materials and Processing Technologies* (2023). Cited by: 0; All Open Access, Green Open Access, Hybrid Gold Open Access. DOI: 10.1080/2374068X.2023.2220242.

[12] R. Ahmed et al. "Influence of Re-HIPing on the structure-property relationships of cobalt-based alloys". In: *Tribology International* 57 (2013). Cited by: 33, pp. 8–21. DOI: 10.1016/j.triboint.2012.06.025.

[13] A. Frenk and W. Kurz. "Microstructural effects on the sliding wear resistance of a cobalt-based alloy". In: *Wear* 174.1-2 (1994). cited By 126, pp. 81–91. DOI: 10.1016/0043-1648(94)90089-2.

[14] J.-H. Song and H.-J. Kim. "Sliding wear performance of cobalt-based alloys in molten-Al-added zinc bath". In: *Wear* 210.1-2 (1997). cited By 30, pp. 291–298. DOI: 10.1016/S0043-1648(97)00092-6.

[15] N.S. McIntyre, D. Zetaruk, and E.V. Murphy. "X-Ray photoelectron spectroscopic study of the aqueous oxidation of stellite-6 alloy". In: *Surface and*

Interface Analysis 1.4 (1979). Cited by: 28, pp. 105–110. DOI: 10.1002/sia.740010402.

[16] Pengxiang Xu et al. "Optimization of process parameters for laser cladding Stellite6 cobalt-based alloy". In: *Materials Today Communications* 38 (2024). Cited by: 1. DOI: 10.1016/j.mtcomm.2024.108430.

[17] Guiyan Gao, Shusheng Guo, and Derui Li. "A Review of Cavitation Erosion on Pumps and Valves in Nuclear Power Plants". In: *Materials* 17.5 (2024). Cited by: 0. DOI: 10.3390/ma17051007.

[18] Diógenes Barbosa Teles et al. "Effect of HVOF spray coating on the tribological surface of onshore gate valves". In: *Wear* 546-547 (2024). Cited by: 0. DOI: 10.1016/j.wear.2024.205322.

[19] Karan Sotoodeh. "Stellite Weld Overlay Qualification on the Body of a Dual Plate Check Valve in Low-Temperature Carbon Steel in the Offshore Oil and Gas Industry". In: *Experimental Techniques* 47.4 (2023). Cited by: 1, pp. 929–938. DOI: 10.1007/s40799-022-00594-1.

[20] Moo-Keun Song et al. "Study on optimization of laser cladding using Stellite 6 powder for exhaust valve face of marine engine". In: *Modern Physics Letters B* 33.14-15 (2019). Cited by: 4. DOI: 10.1142/S0217984919400372.

[21] Yinping Ding et al. "Stellite alloy mixture hardfacing via laser cladding for control valve seat sealing surfaces". In: *Surface and Coatings Technology* 329 (2017). Cited by: 57, pp. 97–108. DOI: 10.1016/j.surfcoat.2017.09.018.

[22] M.A. Ashworth et al. "Microstructure and property relationships in hipped Stellite powders". English. In: *Powder Metallurgy* 42.3 (1999). Cited by: 21, pp. 243–249. ISSN: 00325899. DOI: 10.1179/003258999665585.

[23] C.D. Opris et al. "Development of Stellite alloy composites with sintering/HIPing technique for wear-resistant applications". In: *Materials and Design* 28.2 (2007). cited By 48, pp. 581–591. DOI: 10.1016/j.matdes.2005.08.004.

[24] H. Engqvist et al. "Tribofilm formation on cemented carbides in dry sliding conformal contact". In: *Wear* 239.2 (2000). cited By 83, pp. 219–228. DOI: 10.1016/S0043-1648(00)00315-X.

[25] Kenneth C. Antony. "WEAR-RESISTANT COBALT-BASE ALLOYS." In: *Journal of Metals* 35.2 (1983). cited By 119, pp. 52–60.

[26] P. Crook and A.V. Levy. "Friction and wear of cobalt-base wrought alloys". In: *ASM Handbook* 18 (1992). cited By 18, pp. 766–771.

[27] V.M. Desai et al. "Effect of carbide size on the abrasion of cobalt-base powder metallurgy alloys". In: *Wear* 94.1 (1984). cited By 57, pp. 89–101. DOI: 10.1016/0043-1648(84)90168-6.

[28] L.J. Yang and N.L. Loh. "The wear properties of plasma transferred arc cladded stellite specimens". In: *Surface and Coatings Technology* 71.2 (1995). cited By 30, pp. 196–200. DOI: 10.1016/0257-8972(94)01021-A.

[29] J.L. De Mol Van Otterloo and J.Th.M. De Hosson. "Microstructural features and mechanical properties of a cobalt-based laser coating". In: *Acta Materialia* 45.3 (1997). cited By 97, pp. 1225–1236. DOI: 10.1016/S1359-6454(96)00250-9.

[30] H. Yu, R. Ahmed, and H. de Villiers Lovelock. "A comparison of the tribo-mechanical properties of a wear resistant cobalt-based alloy produced by different manufacturing processes". In: *Journal of Tribology* 129.3 (2007). cited By 30, pp. 586–594. DOI: 10.1115/1.2736450.

[31] Julian Krell, Arne Röttger, and Werner Theisen. "Comprehensive investigation of the microstructure-property relationship of differently manufactured Co–Cr–C alloys at room and elevated temperature". In: *Wear* 444-445 (2020), p. 203138. ISSN: 0043-1648. DOI: https://doi.org/10.1016/j.wear.2019.203138. URL: https://www.sciencedirect.com/science/article/pii/S0043164819312840.

[32] L. Wang et al. "Cavitation-Erosion behavior of laser cladded Low-Carbon Cobalt-Based alloys on 17-4PH stainless steel". In: *Optics and Laser Technology* 158 (2023). cited By 5. DOI: 10.1016/j.optlastec.2022.108761.

[33] M. Szala, D. Chocyk, and M. Turek. “Effect of Manganese Ion Implantation on Cavitation Erosion Resistance of HIPed Stellite 6”. In: *Acta Physica Polonica A* 142.6 (2022). Cited by: 0; All Open Access, Bronze Open Access, pp. 741–746. DOI: 10.12693/APhysPolA.142.741.

[34] Ion Mitelea et al. “Cavitation resistance of Stellite 21 coatings tungsten inert gas (TIG) deposited onto duplex stainless steel X2CrNiMoN22-5-3”. In: *Materialpruefung/Materials Testing* 64.7 (2022). Cited by: 1, pp. 967–976. DOI: 10.1515/mt-2021-2169.

[35] Ji Liu et al. “Effect of corrosion on cavitation erosion behavior of HVOF sprayed cobalt-based coatings”. In: *Materials Research Express* 9.6 (2022). Cited by: 5; All Open Access, Gold Open Access. DOI: 10.1088/2053-1591/ac78c9.

[36] J. Sun et al. “Comparative Study on Cavitation-Resistance and Mechanism of Stellite-6 Coatings Prepared with Supersonic Laser Deposition and Laser Cladding”. In: *Zhongguo Jiguang/Chinese Journal of Lasers* 48.10 (2021). cited By 6. DOI: 10.3788/CJL202148.1002118.

[37] Miroslaw Szala et al. “Effect of nitrogen ion implantation on the cavitation erosion resistance and cobalt-based solid solution phase transformations of HIPed stellite 6”. In: *Materials* 14.9 (2021). Cited by: 20; All Open Access, Gold Open Access, Green Open Access. DOI: 10.3390/ma14092324.

[38] Qunli Zhang et al. “Correlation between microstructural characteristics and cavitation resistance of Stellite-6 coatings on 17-4 PH stainless steel prepared with supersonic laser deposition and laser cladding”. In: *Journal of Alloys and Compounds* 860 (2021). Cited by: 17. DOI: 10.1016/j.jallcom.2020.158417.

[39] D. Mutaşcu et al. “Cavitation resistant layers from stellite alloy deposited by TIG welding on duplex stainless steel”. In: cited By 1. 2019, pp. 776–780.

[40] V.I. Kovalenko et al. “Erosion of co-cr-w alloy and coatings on its basis under cavitation in and”. In: *Problems of Atomic Science and Technology* 2019.5 (2019). cited By 0, pp. 175–178.

[41] M. E et al. “Microstructure and cavitation erosion resistance of cobalt-based and nickel-based coatings”. In: *Cailiao Rechuli Xuebao/Transactions of Materials and Heat Treatment* 39.1 (2018). cited By 7, pp. 90–96. DOI: 10.13289/j.issn.1009-6264.2017-0357.

[42] C.-R. Ciubotariu et al. “Experimental study regarding the cavitation and corrosion resistance of stellite 6 and self-fluxing remelted coatings”. In: *Strojniski Vestnik/Journal of Mechanical Engineering* 62.3 (2016). cited By 12, pp. 154–162. DOI: 10.5545/sv-jme.2015.2663.

[43] R. Singh et al. “Laser cladding of Stellite 6 on stainless steel to enhance solid particle erosion and cavitation resistance”. In: *Surface and Coatings Technology* 251 (2014). cited By 120, pp. 87–97. DOI: 10.1016/j.surfcoat.2014.04.008.

[44] S. Hattor. “Recent investigations on cavitation erosion at the university of fukui”. In: *Fluid Mechanics and its Applications* 106 (2014). cited By 2, pp. 257–282. DOI: 10.1007/978-94-017-8539-6_11.

[45] W. Depczynski and N. Radek. “Properties of elektro sparc deposited stellite coating on mild steel”. In: cited By 3. 2013, pp. 1045–1050.

[46] R. Singh, S.K. Tiwari, and S.K. Mishra. “Cladding of tungsten carbide and stellite using high power diode laser to improve the surface properties of stainless steel”. In: *Advanced Materials Research* 585 (2012). cited By 2, pp. 498–501. DOI: 10.4028/www.scientific.net/AMR.585.498.

[47] S.A. Romo et al. “Cavitation and high-velocity slurry erosion resistance of welded Stellite 6 alloy”. In: *Tribology International* 47 (2012). cited By 68, pp. 16–24. DOI: 10.1016/j.triboint.2011.10.003.

[48] S. Hattori and N. Mikami. “Cavitation erosion resistance of stellite alloy weld overlays”. In: *Wear* 267.11 (2009). cited By 68, pp. 1954–1960. DOI: 10.1016/j.wear.2009.05.007.

[49] S. Guo et al. “Influence of scanning velocity on microstructure and properties of Co-based alloy coatings by diode laser cladding”. In: *Jinshu Rechuli/Heat*

Treatment of Metals 41.8 (2016). cited By 2, pp. 123–127. DOI: 10.13251/j.issn.0254-6051.2016.08.028.

[50] C.-R. Ciubotariu et al. "Optimization of the laser remelting process for HVOF-sprayed Stellite 6 wear resistant coatings". In: *Optics and Laser Technology* 77 (2016). cited By 44, pp. 98–103. DOI: 10.1016/j.optlastec.2015.09.005.

[51] O. Lavigne et al. "Effect of binder nature and content on the cavitation erosion resistance of cemented carbides". In: *International Journal of Refractory Metals and Hard Materials* 109 (2022). cited By 3. DOI: 10.1016/j.ijrmhm.2022.105978.

[52] G. Hou et al. "Cavitation erosion mechanisms in Co-based coatings exposed to seawater". In: *Ultrasonics Sonochemistry* 60 (2020). cited By 31. DOI: 10.1016/j.ultsonch.2019.104799.

[53] J. Liu et al. "Effects of cobalt content on the microstructure, mechanical properties and cavitation erosion resistance of HVOF sprayed coatings". In: *Coatings* 9.9 (2019). cited By 29. DOI: 10.3390/coatings9090534.

[54] H. Zhang et al. "A Comparative Study of Cavitation Erosion Resistance of Several HVOF-Sprayed Coatings in Deionized Water and Artificial Seawater". In: *Journal of Thermal Spray Technology* 28.5 (2019). cited By 29, pp. 1060–1071. DOI: 10.1007/s11666-019-00869-x.

[55] M. E et al. "Comparison of the cavitation erosion and slurry erosion behavior of cobalt-based and nickel-based coatings". In: *Wear* 428-429 (2019). cited By 49, pp. 246–257. DOI: 10.1016/j.wear.2019.03.022.

[56] M.C. Romero, A.P. Tschiptschin, and C. Scandian. "Low temperature plasma nitriding of a Co30Cr19Fe alloy for improving cavitation erosion resistance". In: *Wear* 426-427 (2019). Cited by: 10, pp. 581–588. DOI: 10.1016/j.wear.2019.01.019.

[57] M.C. Romero, A.P. Tschiptschin, and C. Scandian. "Cavitation erosion resistance of a non-standard cast cobalt alloy: Influence of solubilizing and cold

working treatments". In: *Wear* 426-427 (2019). Cited by: 13, pp. 518–526. DOI: 10.1016/j.wear.2018.12.044.

[58] Y. Lei et al. "Cavitation erosion resistance of Co alloy coating on 304 stainless steel by TIG cladding". In: *Hanjie Xuebao/Transactions of the China Welding Institution* 32.7 (2011). cited By 4, pp. 9–12.

[59] C.-P. Qin and Y.-G. Zheng. "Cavitation erosion behavior of a laser clad Co-based alloy on 17-4PH stainless steel". In: *Corrosion Science and Protection Technology* 23.3 (2011). cited By 8, pp. 209–213.

[60] Z.-X. Ding et al. "Research on cavitation erosion resistance of spraying and fusing co-based and Ni-based coatings". In: *Hunan Daxue Xuebao/Journal of Hunan University Natural Sciences* 35.1 (2008). cited By 0, pp. 66–70.

[61] L.-H. Feng, Y.-C. Lei, and X.-J. Zhao. "Cavitation behavior of a Co-base alloy". In: *Corrosion and Protection* 27.11 (2006). cited By 0, pp. 558–560.

[62] R. Ahmed, H.L. de Villiers Lovelock, and S. Davies. "Sliding wear of blended cobalt based alloys". In: *Wear* 466-467 (2021). Cited by: 13. DOI: 10.1016/j.wear.2020.203533.

[63] R. Ahmed and H.L. De Villiers Lovelock. "Friction and Wear of Cobalt-Base Alloys". In: *Frict. Lubr. Wear Technol.* 18 (2017). cited By 8, pp. 487–501.

[64] R. Ahmed et al. "Single asperity nanoscratch behaviour of HIPed and cast Stellite 6 alloys". In: *Wear* 312.1-2 (2014). cited By 41, pp. 70–82. DOI: 10.1016/j.wear.2014.02.006.

[65] R. Ahmed et al. "Structure-property relationships in a CoCrMo alloy at micro and nano-scales". In: *Tribology International* 80 (2014). cited By 20, pp. 98–114. DOI: 10.1016/j.triboint.2014.06.015.

[66] H. Yu et al. "Tribo-mechanical evaluations of cobalt-based (Stellite 4) alloys manufactured via HIPing and casting". In: *Proceedings of the World Congress on Engineering, WCE 2007* 2 (2007). cited By 7, pp. 1385–1390.

[67] H. Yu et al. "Influence of manufacturing process and alloying element content on the tribomechanical properties of cobalt-based alloys". In: *Journal of Tribology* 131.1 (2009). Cited by: 35, pp. 1–12. DOI: 10.1115/1.2991122.

[68] Prashant Kumar, S.K. Singal, and Pankaj P. Gohil. "A technical review on combined effect of cavitation and silt erosion on Francis turbine". In: *Renewable and Sustainable Energy Reviews* 190 (2024). Cited by: 0. DOI: 10.1016/j.rser.2023.114096.

[69] Ji Hui Kim et al. "Effect of manganese on the cavitation erosion resistance of iron-chromium-carbon-silicon alloys for replacing cobalt-base Stellite". In: *Journal of Nuclear Materials* 352.1-3 (2006). Cited by: 15, pp. 85–89. DOI: 10.1016/j.jnucmat.2006.02.072.

[70] "Part III: Corrosion in Water-Bearing Systems". In: *Corrosion Atlas Case Studies*. Ed. by Fuad Khoshnaw and Rolf Gubner. Corrosion Atlas Series. Elsevier, 2022, pp. lxix–lxxxiv. ISBN: 978-0-323-85849-6. DOI: https://doi.org/10.1016/B978-0-323-85849-6.02004-7. URL: https://www.sciencedirect.com/science/article/pii/B9780323858496020047.

[71] Onur Usta, Çağatay Sabri Köksal, and Emin Korkut. "A systematic study into the cavitation erosion test for marine propeller materials by cavitating jet technique". In: *Ocean Engineering* 284 (2023). Cited by: 4. DOI: 10.1016/j.oceaneng.2023.115252.

[72] Feng Cheng et al. "A prediction model for suction cavitation erosion in a journal bearing". In: *Tribology International* 184 (2023). Cited by: 2. DOI: 10.1016/j.triboint.2023.108424.

[73] Renshi Zheng et al. "On the cavitation erosion-corrosion of pipeline steel at different locations of Venturi pipe". In: *Engineering Failure Analysis* 138 (2022). Cited by: 13. DOI: 10.1016/j.engfailanal.2022.106333.

[74] Fei-Jun Chen, Cheng Yao, and Zhen-Guo Yang. "Failure analysis on abnormal wall thinning of heat-transfer titanium tubes of condensers in nuclear power plant Part II: Erosion and cavitation corrosion". In: *Engineering Failure Analysis* 37 (2014). Cited by: 44, pp. 42–52. DOI: 10.1016/j.engfailanal.2013.11.002.

[75] Wahiba Mokrane and Ahmed Kettab. "Flow behaviour analysis through a venturi designed for industrial and environmental processes". In: *Euro-*

Mediterranean Journal for Environmental Integration 4.1 (2019). Cited by: 3. DOI: 10.1007/s41207-018-0093-6.

[76] Haidong Yu et al. "Development of a Novel Nonlinear Dynamic Cavitation Model and Its Numerical Validations". In: *Advances in Applied Mathematics and Mechanics* 16.3 (2024). Cited by: 0; All Open Access, Bronze Open Access, Green Open Access, pp. 771–804. DOI: 10.4208/aamm.OA-2023-0041.

[77] Agnieszka Niedzwiedzka, Günter H. Schnerr, and Wojciech Sobieski. "Review of numerical models of cavitating flows with the use of the homogeneous approach". In: *Archives of Thermodynamics* 37.2 (2016). Cited by: 44; All Open Access, Bronze Open Access, pp. 71–88. DOI: 10.1515/aoter-2016-0013.

[78] Lavinia Madalina Micu, Ilare Bordeasu, and Mircea Octavian Popoviciu. "A new model for the equation describing the cavitation mean depth erosion rate curve". In: *Revista de Chimie* 68.4 (2017). Cited by: 19; All Open Access, Bronze Open Access, pp. 894–898. DOI: 10.37358/rc.17.4.5573.

[79] Moein Talebian Gevari et al. "Direct and indirect thermal applications of hydrodynamic and acoustic cavitation: A review". In: *Applied Thermal Engineering* 171 (2020), p. 115065. ISSN: 1359-4311. DOI: https://doi.org/10.1016/j.applthermaleng.2020.115065.

[80] Lixin Bai et al. "Cavitation in thin liquid layer: A review". In: *Ultrasonics Sonochemistry* 66 (2020). Cited by: 34; All Open Access, Hybrid Gold Open Access. DOI: 10.1016/j.ultsonch.2020.105092.

[81] A. Karimi and J.L. Martin. "Cavitation erosion of materials". In: *International Metals Reviews* 31.1 (1986). cited By 325, pp. 1–26. DOI: 10.1179/imtr.1986.31.1.1.

[82] Y. Meged. "Modeling of the initial stage in vibratory cavitation erosion tests by use of a Weibull distribution". In: *Wear* 253.9-10 (2002). Cited by: 28, pp. 914–923. DOI: 10.1016/S0043-1648(02)00037-6.

[83] Shuji Hattori and Kohei Maeda. "Logistic curve model of cavitation erosion progress in metallic materials". In: *Wear* 268.7-8 (2010). Cited by: 11, pp. 855–862. DOI: 10.1016/j.wear.2009.11.013.

[84] Janusz Steller. "Erosive wear modelling by means of the fractional approach". In: *Wear* 484-485 (2021). Cited by: 2. DOI: 10.1016/j.wear.2021.204015.

[85] Janusz Steller. "Cavitation damage as a result of polyfractional erosion process". In: *Wear* 456-457 (2020). Cited by: 6. DOI: 10.1016/j.wear.2020.203369.

[86] Y. Meged. "Electrical analogy for cavitation erosion test results". In: *Materials Performance and Characterization* 4.1 (2015). Cited by: 3, pp. 262–282. DOI: 10.1520/MPC20150019.

[87] Regiane Fortes Patella et al. "Mass loss simulation in cavitation erosion: Fatigue criterion approach". In: *Wear* 300.1-2 (2013). Cited by: 72, pp. 205–215. DOI: 10.1016/j.wear.2013.01.118.

[88] A. Karimi and W.R. Leo. "Phenomenological model for cavitation erosion rate computation". In: *Materials Science and Engineering* 95 (1987), pp. 1–14. ISSN: 0025-5416. DOI: https://doi.org/10.1016/0025-5416(87)90493-9. URL: https://www.sciencedirect.com/science/article/pii/0025541687904939.

[89] H.C. Meng and K.C. Ludema. "Wear models and predictive equations: their form and content". In: *Wear* 181-183.PART 2 (1995). cited By 822, pp. 443–457. DOI: 10.1016/0043-1648(95)90158-2.

[90] N. Berchiche, J.P. Franc, and J.M. Michel. "A cavitation erosion model for ductile materials". In: *Journal of Fluids Engineering, Transactions of the ASME* 124.3 (2002). Cited by: 52; All Open Access, Green Open Access, pp. 601–606. DOI: 10.1115/1.1486474.

[91] Y. Meged. "Modeling of vibratory cavitation erosion test results by a Weibull distribution". In: *Journal of Testing and Evaluation* 31.4 (2003). Cited by: 9, pp. 277–288.

[92] Hitoshi Soyama and Masatoshi Futakawa. "Estimation of incubation time of cavitation erosion for various cavitating conditions". In: *Tribology Letters* 17.1 (2004). Cited by: 24, pp. 27–30. DOI: 10.1023/B:TRIL.0000017415.79517.8c.

[93] Y. Meged. "On the anomaly of cumulative erosion and abrasion-time curves". In: *Journal of Testing and Evaluation* 34.1 (2006). Cited by: 3, pp. 42–52.

[94] *Standard Test Method for Cavitation Erosion Using Vibratory Apparatus.* Standard. ASTM International, June 2021.

[95] F.G. Hammitt. *Cavitation and multiphase flow phenomena.* cited By 357. 1980.

[96] K. Endo, T. Okada, and M. Nakashima. "A study of erosion between two parallel surfaces oscillating at close proximity in liquids". In: *Journal of Tribology* 89.3 (1967). Cited by: 13, pp. 229–236. DOI: 10.1115/1.3616956.

[97] Kinya Kikuchi and Frederick G. Hammitt. "Effect of separation distance on cavitation erosion of vibratory and stationary specimens in a vibratory facility". In: *Wear* 102.3 (1985). Cited by: 16, pp. 211–225. DOI: 10.1016/0043-1648(85)90219-4.

[98] Y. Me-Bar. "On cavitation in thin liquid layers". In: *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 452.1947 (1996). Cited by: 6, pp. 741–755. DOI: 10.1098/rspa.1996.0037.

[99] A. Abouel-Kasem and S.M. Ahmed. "Bubble structures between two walls in ultrasonic cavitation erosion". In: *Journal of Tribology* 134.2 (2012). Cited by: 13, 21702–1 – 21702–9. DOI: 10.1115/1.4005217.

[100] Pengfei Wu et al. "Stability of cavitation structures in a thin liquid layer". In: *Ultrasonics Sonochemistry* 38 (2017). Cited by: 32, pp. 75–83. DOI: 10.1016/j.ultsonch.2017.03.002.

[101] B.G. Singer and S.J. Harvey. "Gas content and temperature effects in vibratory cavitation tests". In: *Wear* 52.1 (1979). Cited by: 22, pp. 147–160. DOI: 10.1016/0043-1648(79)90205-9.

[102] S.M. Ahmed. "Investigation of the temperature effects on induced impact pressure and cavitation erosion". In: *Wear* 218.1 (1998). Cited by: 43, pp. 119–127. DOI: 10.1016/S0043-1648(97)00290-1. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032525746&doi=10.1016%2fS0043-1648%2897%2900290-1&partnerID=40&md5=5ad9d9a293061e8c7a5f6f7b9874

[103] Kewen Peng et al. "Interpreting the influence of liquid temperature on cavitation collapse intensity through bubble dynamic analysis". In: *Ultrasonics Sonochemistry* 69 (2020). Cited by: 31. DOI: 10.1016/j.ultsonch.2020.105253. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85088657457&doi=10.1016%2fj.ultsonch.2020.105253&partnerID=40&md5=5942a0fa31a67217d5936aeb31d83252.

[104] Arun Prasanth Nagalingam and S.H. Yeo. "Effects of ambient pressure and fluid temperature in ultrasonic cavitation machining". In: *International Journal of Advanced Manufacturing Technology* 98.9-12 (2018). Cited by: 27, pp. 2883–2894. DOI: 10.1007/s00170-018-2481-0.

[105] Abhinav Priyadarshi et al. "Effect of water temperature and induced acoustic pressure on cavitation erosion behaviour of aluminium alloys". In: *Tribology International* 189 (2023). Cited by: 2; All Open Access, Green Open Access, Hybrid Gold Open Access. DOI: 10.1016/j.triboint.2023.108994.

[106] J.-C. Shin et al. "Effect of molybdenum on the microstructure and wear resistance of cobalt-base Stellite hardfacing alloys". In: *Surface and Coatings Technology* 166.2-3 (2003). cited By 181, pp. 117–126. DOI: 10.1016/S0257-8972(02)00853-8.

[107] W.V. Youdelis and O. Kwon. "Carbide phases in cobalt base superalloy: Role of nucleation entropy in refinement". In: *Metal Science* 17.8 (1983). cited By 23, pp. 379–384. DOI: 10.1179/030634583790420664.

[108] Paul Crook. "Cobalt-base alloys resist wear, corrosion, and heat". In: *Advanced Materials and Processes* 145.4 (1994). cited By 22, pp. 27–30.

[109] C.J. Heathcock, A. Ball, and B.E. Protheroe. "Cavitation erosion of cobalt-based Stellite® alloys, cemented carbides and surface-treated low alloy steels".

In: *Wear* 74.1 (1981). Cited by: 70, pp. 11–26. DOI: 10.1016/0043-1648(81)90191-5.

[110] C.M. Garzón et al. "Cavitation erosion resistance of a high temperature gas nitrided duplex stainless steel in substitute ocean water". In: *Wear* 259.1-6 (2005). cited By 33, pp. 145–153. DOI: 10.1016/j.wear.2005.02.005.

[111] U. Malayoglu and A. Neville. "Comparing the performance of HIPed and Cast Stellite 6 alloy in liquid–solid slurries". In: *Wear* 255.1 (2003). 14th International Conference on Wear of Materials, pp. 181–194. ISSN: 0043-1648. DOI: https://doi.org/10.1016/S0043-1648(03)00287-4.

[112] Kamal E. Mohamed et al. "Localized corrosion behaviour of powder metallurgy processed cobalt-base alloy Stellite-6 in chloride environments". In: *Zeitschrift fuer Metallkunde/Materials Research and Advanced Techniques* 90.3 (1999). Cited by: 21, pp. 195–201. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032644980&partnerID=40&md5=058e899a9663318544d8e5149c9acd4a.

[113] Zonglian Huang et al. "Microstructure evolution, martensite transformation and mechanical properties of heat treated Co-Cr-Mo-W alloys by selective laser melting". In: *International Journal of Refractory Metals and Hard Materials* 113 (2023), p. 106170. ISSN: 0263-4368. DOI: https://doi.org/10.1016/j.ijrmhm.2023.106170. URL: https://www.sciencedirect.com/science/article/pii/S0263436823000707.

[114] Pierre-Antoine Dubos et al. "Temperature effect on strain-induced phase transformation of cobalt". In: *Materials Letters* 281 (2020), p. 128812. ISSN: 0167-577X. DOI: https://doi.org/10.1016/j.matlet.2020.128812. URL: https://www.sciencedirect.com/science/article/pii/S0167577X20315196.

[115] Krishna Rajan. "Phase transformations in a wrought Co-Cr-Mo-C alloy". In: *Metallurgical Transactions A* 13.7 (1982). Cited by: 79, pp. 1161–1166. DOI: 10.1007/BF02645497.

[116] H.M. Tawancy, V.R. Ishwar, and B.E. Lewis. "On the fcc → hcp transformation in a cobalt-base superalloy (Haynes alloy No. 25)". In: *Journal*

of Materials Science Letters 5.3 (1986). Cited by: 40, pp. 337–341. DOI: 10.1007/BF01748098.

[117] J.L. De Mol Van Otterloo and J.Th.M. De Hosson. "Microstructure and abrasive wear of cobalt-based laser coatings". In: *Scripta Materialia* 36.2 (1997). cited By 43, pp. 239–245. DOI: 10.1016/S1359-6462(96)00346-6.

[118] Lin Liu, Jun Zhang, and Cheng Ai. "Nickel-Based Superalloys". In: *Encyclopedia of Materials: Metals and Alloys.* Ed. by Francisca G. Caballero. Oxford: Elsevier, 2022, pp. 294–304. ISBN: 978-0-12-819733-2. DOI: https://doi.org/10.1016/B978-0-12-803581-8.12093-4. URL: https://www.sciencedirect.com/science/article/pii/B9780128035818120934.

[119] E. Vacchieri et al. "Service induced fcc→hcp martensitic transformation in a Co-based superalloy". In: *Materials Science and Technology (United Kingdom)* 33.9 (2017). Cited by: 7, pp. 1100–1107. DOI: 10.1080/02670836.2016.1273866.

[120] S Kapoor et al. "Microstructure and wear resistance relations of Stellite alloys". In: *Inter. J. Adv. Mater. Sci.* 4.3 (2013), pp. 231–248.

[121] J.L. De Brouwer and D. Coutsouradis. "Influence of tungsten and carbon contents on the microstructure and properties of a cobalt-base hardfacing alloy". In: *Cobalt* 32 (1966). cited By 12, pp. 141–147.

[122] P. Crook. "Cobalt and cobalt alloys". In: *ASM Handbook* 2.10 (1990). cited By 57, pp. 446–454.

[123] H.V. Atkinson and S. Davies. "Fundamental aspects of hot isostatic pressing: An overview". In: *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science* 31.12 (2000). Cited by: 563, pp. 2981–3000. DOI: 10.1007/s11661-000-0078-2.

[124] H. Yu. "The Microstructure and Tribo-mechanical Properties of HIPed Stellite Alloys". In: (2007). cited By 1.

[125] W.-B. Li, M.F. Ashby, and K.E. Easterling. "On densification and shape change during hot isostatic pressing". In: *Acta Metallurgica* 35.12 (1987). cited By 86, pp. 2831–2842. DOI: 10.1016/0001-6160(87)90282-3.

[126] M.A. Ashworth, M.H. Jacobs, and S. Davies. "Basic mechanisms and interface reactions in HIP diffusion bonding". In: *Materials and Design* 21.4 (2000). Cited by: 20, pp. 351–358. DOI: 10.1016/s0261-3069(99)00088-6.

[127] H.V. Atkinson and B.A. Rickinson. In: *Hot Isostatic Pressing* (1991). cited By 17.

[128] E.K.H. Li and P.D. Funkenbusch. "Hot isostatic pressing (HIP) of powder mixtures and composites: Packing, densification, and microstructural effects". In: *Metallurgical Transactions A* 24.6 (1993). cited By 36, pp. 1345–1354. DOI: 10.1007/BF02668202.

[129] E.K.H. Li and P.D. Funkenbusch. "Modeling of the densification rates of monosized and bimodal-sized particle systems during hot isostatic pressing (HIP)". In: *Acta Metallurgica* 37.6 (1989). cited By 37, pp. 1645–1655. DOI: 10.1016/0001-6160(89)90131-4.

[130] M.V. Speight and G.W. Greenwood. "Grain boundary mobility and its effects in materials containing inert gases". In: *Philosophical Magazine* 9.100 (1964). cited By 57, pp. 683–689. DOI: 10.1080/14786436408211880.

[131] R.L. Coble. "Diffusion models for hot pressing with surface energy and pressure effects as driving forces". In: *Journal of Applied Physics* 41.12 (1970). cited By 357, pp. 4798–4807. DOI: 10.1063/1.1658543.

Appendix A

Risk Assessments

The following risk assessments are:

- Grinder-Polisher A.1
- Ultrasonic Bath A.2
- Cavitation Equipment A.3

A.1 Risk Assessment - Grinder Polisher

Risk Assessment Title: Grinder-Polisher	Ref No: 2023-2024

School/Institute/Directorate:	Location:	Supervisor	Date:	Review Date:
EPS	Energy Lab, Dubai	Dr Rehan Ahmed	2023-09-11	Whenever there is a change in SOP and risk involved. Last update: 2023-09-11

Risk Rating Matrix (RR)	**Likelihood(L)**		
Severity (S)	**Certain or near certain to occur (High)**	**Reasonably likely to occur (Medium)**	**Unlikely to Occur (Low)**
Fatality, major injury or illness causing long term disability (High)	**HIGH(H)**	**HIGH(H)**	**MEDIUM(M)**
Injury or illness causing short term disability (Medium)	**HIGH(H)**	**MEDIUM(M)**	**LOW(L)**
Other Injury or Illness (Low)	**MEDIUM(M)**	**LOW(L)**	**LOW(L)**

Description:

Background:

Metallographic samples often need to be grinded down and polished before use in experiments; the surface with unaccounted for roughness may experience faster rates of corrosion and erosion. The Buelher grinder-polisher is used to prepare samples in-house.

In this procedure, the grinder-polisher is supplied with electrical and compressed air supply. Electrical power is used to power the motor and interface while compressed air is used to apply controlled amounts of force to workpieces. The workpiece holder and base plate rotate, in order to provide uniform grinding and polishing action to all workpieces.

Personal Protective Equipment (PPE)

Wear gloves and lab coat with folded sleeves while using grinder polisher. Enclosed shoes must be worn while using the machine. Avoid entanglement of hair with hairband.

Procedural Controls

Care should be taken to avoid operating equipment unless properly trained.

Avoid accessing the rear of instrument.

Low stocks of consumable items (gloves, paper towels, etc) should be reported to Supervisor or Lab Manager.

What are the Hazards?	Who might be harmed?	Uncontrolled Risk Rating	Control measures (What are you already doing?)	Controlled Risk Rating	Responsible Person(s)
Rotating mechanisms	Equipment User Lab User	High	Users are trained and supervised until fully competent. Users are trained to not access mechanical parts of the grinder-polisher while running. Sample holder and platen have grooves cut into them for easier removal of consumables from equipment.	Medium	Equipment User Supervisor
Electric Shock	Equipment User Lab User	High	Use of waterproof electrical socket for electrical connection. Avoid touch of electrical source and connections using wet hands. Keep hands dry whenever touch the electrical source. Switch off the ultrasonic probe when not in use. Check PAT testing is up to date.	Low	Equipment User
Hand, Hair, or Clothing entanglement	Equipment User Lab User	Medium	Long hair and loose clothing should be secured to avoid contact with moving parts. Users must wear lab coat with folded sleeves, as well as nitrile gloves. Jewellery (eg. rings) should be removed.	Low	Equipment User Supervisor
Contact with lubricants	Equipment User	Low	Avoid touching cutting lubricants and pastes. Use of nitrile gloves should control this; MSDS does not list short-term risks. Wash hands if lubricants come into contact with hands.	Low	Equipment User

Additional Work Practice Information:

If Lab Users are sensitive to noise or poor quality air, avoid use of equipment.
Ensure that compressed air supply is available when using equipment.
Facilities Management and Housekeeping usually do not touch equipment. Keep space around cavitation equipment clean to avoid interference.
Avoid use of grinder-polisher when classes occur in the lab. Avoiding noise disturbance is a courtesy worth extending to other lab users.

	Name	Position	Email	Signature
Author	Vishakh Pradeep Kumar	MSc Student; Research Assistant	v.kumar@hw.ac.uk	Vishakh Pradeep Kumar
Authoriser	Dr Rehan Ahmed	Supervisor	r.ahmed@hw.ac.uk	
Verifier				

Declaration

I confirm that I have read the Risk Assessment, I understand the hazards, and risks involved and will follow all the control measures stated. If I have any queries or concerns, I will contact the above.

Name	Organisation	Staff/Student/Visitor	Signature	Date
Vishakh Pradeep Kumar	EPS	Student	Vishakh Pradeep Kumar	2023-09-11

A.2 Risk Assessment - Ultrasonic Bath

Risk Assessment Title: Ultrasonic Bath & related	Ref No: 2023-2024

School/Institute/Directorate:	Location:	Supervisor	Date:	Review Date:
EPS	Energy Lab, Dubai	Dr Rehan Ahmed	2023-09-11	Whenever there is a change in SOP and risk involved. Last update: 2023-09-11

Risk Rating Matrix (RR)	Likelihood(L)		
Severity (S)	Certain or near certain to occur (High)	Reasonably likely to occur (Medium)	Unlikely to Occur (Low)
Fatality, major injury or illness causing long term disability (High)	HIGH(H)	HIGH(H)	MEDIUM(M)
Injury or illness causing short term disability (Medium)	HIGH(H)	MEDIUM(M)	LOW(L)
Other Injury or Illness (Low)	MEDIUM(M)	LOW(L)	LOW(L)

Description:

Background:

In the creation and analysis of metallographic samples, it is necessary to clean said samples between activities.
The ultrasonic bath is a benchtop device that uses ultrasound energy within liquids to remove residual material from the surface of samples.
Acetone is often used due to its superior cleaning properties and its quick evaporation, allowing for faster cleaning, and drying of samples before weighing.
Acetone can be found in the Flammable cupboard (further details below on use) if not available at ultrasonic bath station.

Personal Protective Equipment (PPE)

Wear gloves, safety glasses, and lab coat while using chemicals (eg. Acetone). Enclosed shoes must be worn while using the machine.

Procedural Controls

Avoid using finger
Consult Material Safety Datasheet (MSDS) before using machine and during training.
Users should operate the bath in accordance with training to avoid damage to the instrument. Avoid accessing the rear of instrument.
Fill bath with clean/distilled water only.
Low stocks of consumable items (gloves, paper towels, etc) should be reported to Supervisor or Lab Manager.

What are the Hazards?	Who might be harmed?	Uncontrolled Risk Rating	Control measures (What are you already doing?)	Controlled Risk Rating	Responsible Person(s)
Fumes	Equipment User	Low	Use of well-ventilated space.	Low	Lab Manager
Noise	Equipment User Lab User	Low	Avoid using ultrasonic cleaner while using nearby equipment. Use of ear protection.	Low	Equipment User Supervisor
Electric Shock	Equipment User Lab User	High	Use of waterproof electrical socket for electrical connection. Avoid touch of electrical source and connections using wet hands. Keep hands dry whenever touch the electrical source. Switch off the ultrasonic cleaner when not in use. PAT Test equipment yearly.	Low	Lab Manager
Using flammable solvents in ultrasonic cleaner	Equipment User Lab User	Medium	The ultrasonic bath is not to be filled with flammable solvents (eg. IPA, acetone) as flammable solvents pose a serious explosion hazard. Small parts are to be cleaned inside beakers that are partially immersed in water – the waves pass through the beakers wall.	Low	Equipment User Supervisor
Storage of flammable chemicals	Equipment User	High	Ensure that large quantities of acetone are stored in the flammable liquids cupboard in the Chemical lab and that only small quantities are utilized near the station. In the event of a spill, avoid use of nearby equipment without removing spilled liquid.	Low	Equipment User
Cuts from broken glass	Equipment User	Low	Avoid using chipped or broken glassware. Use nitrile gloves while handling acetone. Avoid touching broken glass with bare hands.	Low	Equipment User

Additional Work Practice Information:
Avoid use of beakers on bottom of ultrasonic bath tank; the vibration induced may wear the tank surface leading to leaks and damage.
If Equipment Users are sensitive to noise or poor quality air, avoid use of uncovered operation of ultrasonic cleaner and use N95 masks.
Facilities Management and Housekeeping usually do not touch equipment. Keep space around ultrasonic equipment clean to avoid interference.
Avoid use of ultrasonic cleaner when classes occur in the lab. Although inconvenient, avoiding noise disturbance is a courtesy worth extending to other lab users.

	Name	Position	Email	Signature
Author	Vishakh Pradeep Kumar	MSc Student; Research Assistant	v.kumar@hw.ac.uk	Vishakh Pradeep Kumar
Authoriser	Dr Rehan Ahmed	Supervisor	r.ahmed@hw.ac.uk	
Verifier				

Declaration

I confirm that I have read the Risk Assessment, I understand the hazards, and risks involved and will follow all the control measures stated. If I have any queries or concerns, I will contact the above.

Name	Organisation	Staff/Student/Visitor	Signature	Date
Vishakh Pradeep Kumar	EPS	Student	Vishakh Pradeep Kumar	2023-09-11

A.3 Risk Assessment - Cavitation Equipment

Risk Assessment Title: Cavitation Equipment	Ref No: 2023-2024

School/Institute/Directorate:	Location:	Supervisor	Date:	Review Date:
EPS	Energy Lab, Dubai	Dr Rehan Ahmed	2023-09-11	Whenever there is a change in SOP and risk involved. Last update: 2023-09-11

Risk Rating Matrix (RR)	**Likelihood(L)**		
Severity (S)	**Certain or near certain to occur (High)**	**Reasonably likely to occur (Medium)**	**Unlikely to Occur (Low)**
Fatality, major injury or illness causing long term disability (High)	**HIGH(H)**	**HIGH(H)**	**MEDIUM(M)**
Injury or illness causing short term disability (Medium)	**HIGH(H)**	**MEDIUM(M)**	**LOW(L)**
Other Injury or Illness (Low)	**MEDIUM(M)**	**LOW(L)**	**LOW(L)**

Description:

Background:

An ultrasonic probe is used to simulate the effect of cavitation on metallographic samples. In this procedure, the ultrasonic probe is supplied with electrical and compressed air supply. Electrical power is used to power piezoelectric transducers while compressed air is used to keep the ultrasonic probe cool during extended periods of operation. Either seawater or water is used in the equipment tank to analyse the synergy between the cavitation and corrosion.
Use of this equipment often requires use of the ultrasonic bath and analytical scale.

Personal Protective Equipment (PPE)

Wear gloves and lab coat while using cavitation equipment. Enclosed shoes must be worn while using the machine.

Procedural Controls

Care should be taken to avoid acoustic coupling with human body; avoid immersing hands during operation and use guards to prevent hand access.
Users should operate the bath in accordance with training to avoid damage to the instrument. Avoid accessing the rear of instrument.
Low stocks of consumable items (gloves, paper towels, etc) should be reported to Supervisor or Lab Manager.

What are the Hazards?	Who might be harmed?	Uncontrolled Risk Rating	Control measures (What are you already doing?)	Controlled Risk Rating	Responsible Person(s)
Noise	Equipment User Lab User	Medium	Avoid using cavitation equipment while using nearby equipment. Always wear hearing protection when the ultrasonic probe is in use – applies to all lab users.	Low	Equipment User Supervisor
Electric Shock	Equipment User Lab User	High	Use of waterproof electrical socket for electrical connection. Avoid touch of electrical source and connections using wet hands. Keep hands dry whenever touch the electrical source. Switch off the ultrasonic probe when not in use.	Low	Equipment User
Misuse of ultrasonic probe	Equipment User Lab User	Medium	Ultrasonic probe can be damaged if misused.	Low	Equipment User Supervisor

Additional Work Practice Information:
If Equipment Users are sensitive to noise or poor quality air, avoid use of equipment.
Facilities Management and Housekeeping usually do not touch equipment. Keep space around cavitation equipment clean to avoid interference.
Avoid use of cavitation equipment when classes occur in the lab. Avoiding noise disturbance is a courtesy worth extending to other lab users.

	Name	Position	Email	Signature
Author	Vishakh Pradeep Kumar	MSc Student; Research Assistant	v.kumar@hw.ac.uk	Vishakh Pradeep Kumar
Authoriser	Dr Rehan Ahmed	Supervisor	r.ahmed@hw.ac.uk	
Verifier				

Declaration

I confirm that I have read the Risk Assessment, I understand the hazards, and risks involved and will follow all the control measures stated. If I have any queries or concerns, I will contact the above.

Name	Organisation	Staff/Student/Visitor	Signature	Date
Vishakh Pradeep Kumar	EPS	Student	Vishakh Pradeep Kumar	2023-09-11