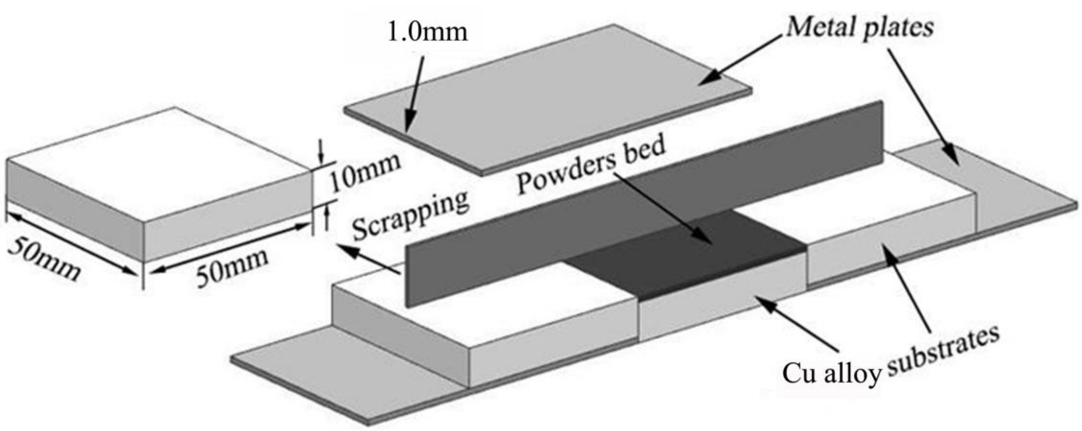
REPORT TITLE: Propeller Performance Enhancement for Ice-going Ships

Project acronym: PROFFS
Project title: Propeller Performance Enhancement for Ice-going Ships
(Förbättrad propellerprestanda för isgående fartyg)



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Contents

1 Executive summary

Maritime traffic has increased in the Baltic Sea as well in the Arctic Sea in recent years. As the climate becomes warmer this trend is expected to continue. It is expected that more ships designed for open-water operations will enter ice-infested waters and propeller damages due to ice-propeller interactions become inevitable. Upgrading the propeller ice class should however be avoided because it is at the cost of the propulsion efficiency. In this pre-study project, we aimed to improve a propeller's ice performance while keeping its open-water profile through implementing laser surface treatment on the propeller blades. Numerical simulations and experiments were carried out. It was found that laser cladding treatment has great potential to improve the propeller performance.

2 Introduction

Maritime traffic has increased in the Baltic Sea as well in the Arctic Sea in recent years. As the climate becomes warmer this trend is expected to continue. Statistics shows that for ice-going vessels propeller damages are predominant among all ice navigation incidents. Upgrading the propeller ice class should however be avoided because it is at the cost of the propulsion efficiency. Instead, in this project, we target at enhancing a propeller's ice performance while keeping its open-water profile. This is supposed to be achieved by implementing laser surface treatment on the propeller blades. The proposed procedure is expected to improve energy efficiency of Swedish ships and thus boost the competitiveness of Swedish shipping industry. Meanwhile, the knowledge gained in this study is expected to be beneficial for developing next generation Swedish icebreakers.

The PROFFS project was a joint pre-study research project between Chalmers University of Technology and Kongsberg Maritime Sweden AB (the previous Rolls-Royce Marine AB). In this study, the laser cladding process was first simulated using numerical methods. Based on the numerical simulation outcome, we chose the proper cladding material and decided the profile of the substrate specimens. The laser cladding process was conducted experimentally, and the material properties of the cladding layer were examined using advanced technologies like X-Ray Diffraction (XRD), Optical Microscope (OM), Scanning Electron Microscope (SEM), and Energy Dispersive Spectrometer (EDS). The numerical and experimental results indicate that laser cladding on propeller blade has potential to improve the propeller performance significantly.

3 Numerical analyses

In the PROFFS project, numerical models based on shakedown limits theory were assumed and Finite Element (FE) analyses were carried out using ABAQUS. Based on the results of the literature study, coating materials suitable for marine applications such as Stellite was selected and modelled in combination of various types of substrate materials. The numerical analyses were carried out using coupled thermo-mechanical simulations of cladding and grinding process. At first, the thermal analysis was carried out to find the nodal temperatures which are obtained as an output database file. This file was used as input for the mechanical analysis which acts as the thermal loads. Though the stresses and strain generated during the mechanical simulations were influenced by the results of thermal analysis, the temperatures are not at all influenced by any stresses. The cladding process was followed by the grinding process which was carried out in ABAQUS as well. Figure 1 illustrates the schematic numerical procedure of the sequentially coupled thermo-mechanical simulations of Cladding and Grinding Processes.

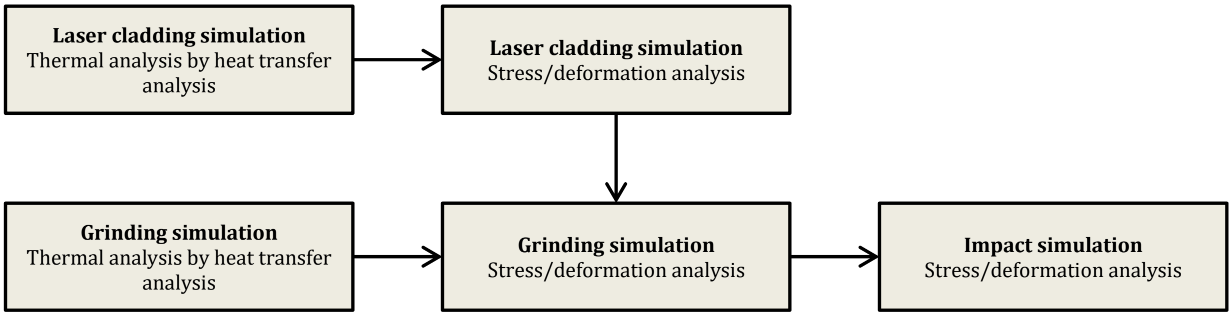

Fig.1: schematic numerical procedure of the sequentially coupled thermo-mechanical simulations of Cladding and Grinding Processes.

3.1 The FE models

The FE models of the substrate and cladding layers were built. Both 3D and 2D models were built and FE analyses were conducted. The 3D simulations take significantly longer computation recourses than the 2D models. It was found that a 2D model is in general sufficient to simulate the cladding process with respect to temperature development and residual stress distribution. The 2D models were thus utilized in most of the simulations, while the 3D model was only assumed in the step of heat transfer. Figure 2 shows the 3D (upper) and 2D (lower) FE models used in the numerical analyses.

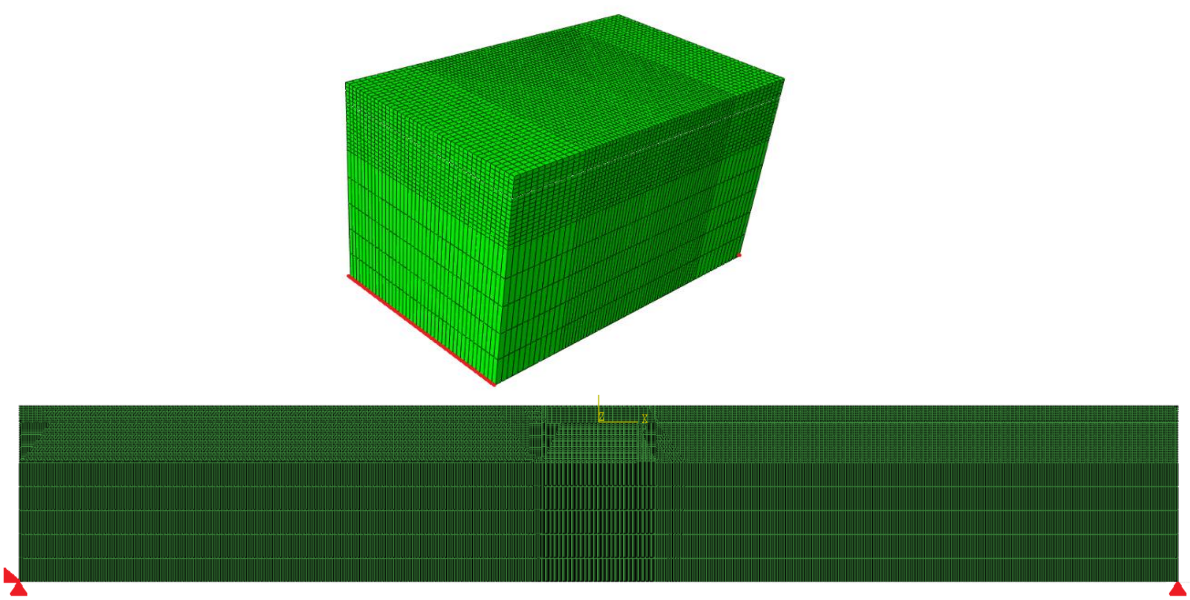

Fig.2: the 3D (upper) and 2D (lower) FE models used in the numerical analyses.

3.2 Cladding simulation

The initial steps of in the thermal and mechanical analyses include the deactivation of all elements of the cladding layer by using a technique called ‘death of elements’, known as model change option in ABAQUS. Then, the thermal simulation began with preheating the substrate which contributed to reduction of temperature gradient for the upcoming blocks. In the following, each block was deposited one after another at steps which signify the cladding process along with the application of uniformly distribute heat source as prescribed node temperatures on the same block. Once all the cladding blocks were deposited, the cooling step was carried out to bring the cladding layer to room temperature.

Four temperature cycles were considered because the successive cladding tracks conduct heat in transverse directions. The temperature of the first cladding cycle was 1500℃ which is more than the melting point of the substrate material. The temperature of the second cladding cycle was 1500℃ and due to the conduction of heat in transverse directions on first cladding track, it was guessed to drop to 1150℃. As the cladding speed increases, the cooling rate also increases. But, the cooling rate decreases with increase in preheating temperature. The effect of heat from the successive third and fourth cladding tracks was presumed to be 400℃. The field outputs were requested at each step to get the nodal temperatures for four different temperature cycles. This was found in an object database file (.odb) after thermal simulation and this file was used in predefined fields as the thermal loads during mechanical simulation of the cladding process. Figure 3 shows an example of the temperature distribution for deposition of 20th block for first track for the substrate of NAB.

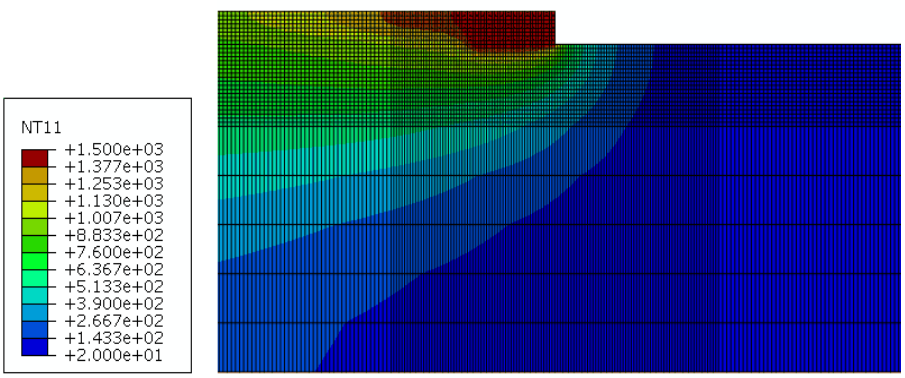

Fig.1: Temperature distribution for deposition of 20th block for first track

The cladding process results in a permanent location of residual stress, strain, and distortion in the components. In the FE mechanical simulations, the mechanical boundary conditions were defined in the initial steps. Further, the thermal loads were extracted from the .odb file of thermal analysis in the form of nodal temperatures which acts as actual loads required for mechanical analysis. In addition, the thermal loads were read from the .odb file and were applied to each node in that particular step. This continued for all the 40 blocks which showed the actual cladding process which is a simultaneous application of heat and cladding powder or wire. This completes the mechanical simulation and the new .odb file was generated to get the outputs of mechanical analysis which are longitudinal and shear residual stresses. These residual stresses were used for further analysis to investigate the effectiveness of cladding layer formed. The longitudinal residual stresses (S11) determines the nature (tensile or compressive) of stresses to estimate the life of substrate after laser cladding and the shear residual stresses (S12) determines the bonding of both substrate and cladding at microstructure level for better performance. Figure 4 shows the distribution of the normal S11 stress in the cladded NAB substrate through thickness between 0 and 5 mm.

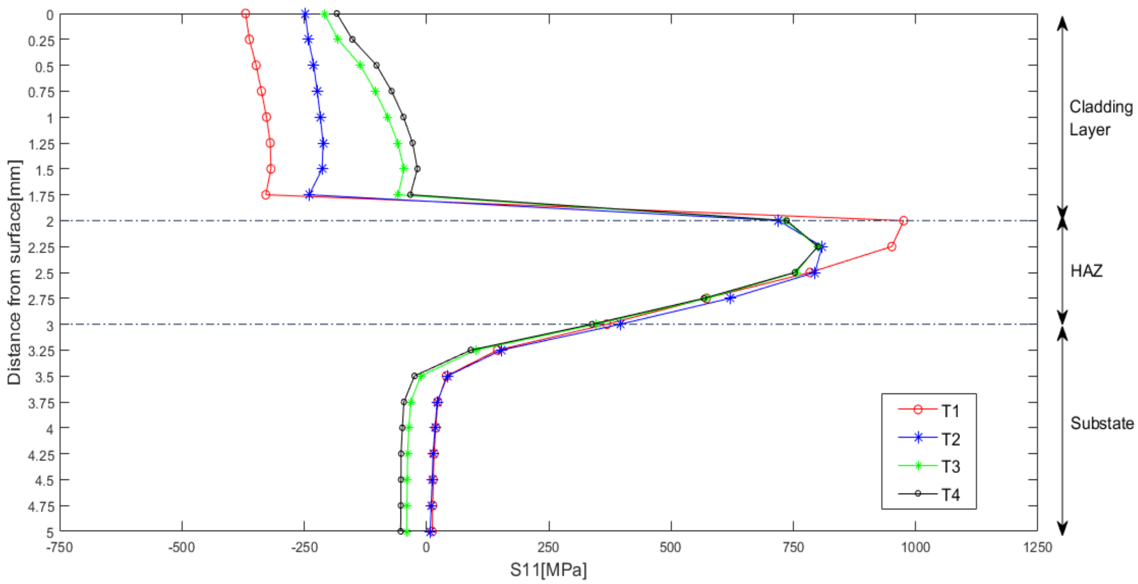

Fig.4: the distribution of S11 stress in the cladded NAB substrate

3.3 Grinding process

The cladding process followed by the grinding process were simulated using sequentially coupled thermo-mechanical approaches. The grinding process includes the application of grinding forces on the cladding layer, which is done with the help of grinding wheel which applies the grinding forces of both the normal pressure and the traction load on the cladding layer. Also, heat is generated due to the friction between the grinding wheel and the cladding layer. The entire grinding process has both mechanical and thermal effects on the cladding layer.

The grinding process has various variables such as grinding wheel diameter, the material of grinding wheel, the speed of the wheel, the depth of cut, the power of the motor used for grinding wheel and others. Hence it was necessary to find an appropriate method to simulate the grinding of the cladding layer in continuation with the previous cladding simulation. At first, the uniform rectangular heat flux distribution was applied in the form of boundary conditions which signifies the heat generated due to the friction and other grinding forces. Next was to generate the effects of grinding forces which includes the normal pressure (contact load) and tangential stress (traction load). This was achieved by applying these two stresses in the form of loads at each point of contact between the wheel and the cladding layer. Because it is required to grind the previously cladding layer which requires the cladding model from previous simulations. To achieve this, the output database file (.odb) which has both the thermal and mechanical simulation file of overall cladding process was used as an input for the simulation of mechanical analysis of the grinding process. Also, as mentioned above the heat generated due to the frictional effect of grinding forces have to be taken into account in the analyses. So, the separate thermal analysis was carried out on the combined model of cladding and substrate with the predefined temperature (magnitude of the rectangular heat flux) that will be explained in upcoming sections.

It is concluded that the grinding process reduces the residual stress. For instance, Figure 4 shows the S11 residual stress distribution in thickness direction from the top surface. The pattern remains quite similar after cladding and grinding process. For this material, residual stress is reduced a bit and is became more compressive at the interface at the end of grinding process compared to cladding process and grinding forces induced increment in residual tensile stresses in HAZ region. Later, residual stress magnitude is fallen gradually and is became compressive in substrate region.

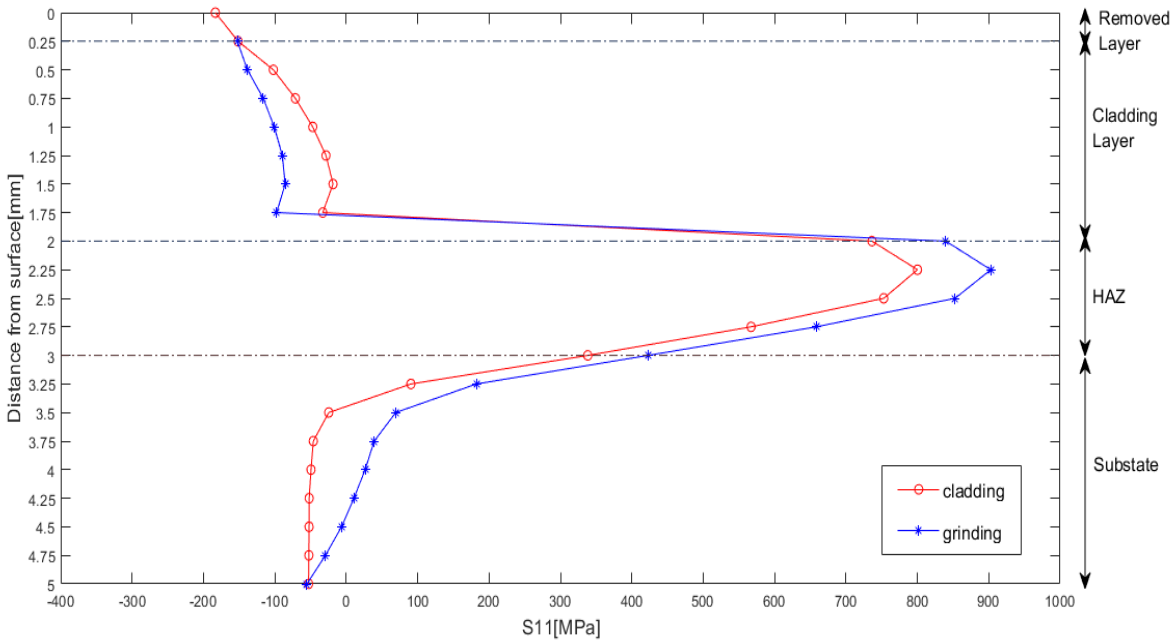

Fig.5: the S11 residual stress distribution in thickness direction from the top surface

4 Experiments

The experimental studies were carried out together with researchers in Shanghai University of Engineering Science (SUES). The Institute of Laser Industrial Technology in SUES is a leading research institute in laser surface treatment. The labs are equipped with various types of laser generators and advanced measurement facilities. The laser cladding experiments in this study were carried out using a 4.5kW Nd:YAG laser generator, as shown in Figure 6.

Fig.6: the 4.5kW Nd:YAG laser generator used in this study

Based on the findings from the literature study as well as the numerical analysis results, we selected scaled test specimens of propeller material and coating material to perform laser surface cladding experiments. The substrate material used in this study is a Nickel Aluminum Bronze alloy C95800 that is composed of Cu: 80, Al: 8.5, Ni: 4.5, Fe: 4.5, Mn: 2.5. C95800 is widely used in marine applications. The substrate specimens are in the size of 50mm×50mm×10mm, manufactured through wire cutting and processed through sandblasting to remove the surface oxide. A pre-welding test was carried out to find out the optimal combination of the scanning speed and the laser beam diameter, which led to the cladding setup as presented as following. The test specimens after the pre-welding test are shown in Figure 7.

- Nd: YAG (HV-V1-400)
- Argon gas protection (20 L/min)
- Power: 4500 W
- Frequency: 60 Hz
- Laser beam diameter: 2 mm
- Scan speed:10 mm/s

Fig.7: the test specimens from the pre-welding test.

The cladding material is a mixture of TaC reinforced phase and Co-based alloy Stellitex-40. The Chemical composition ratio of Stellitex-40 is shown in Table 1, while the various weight ratio of TaC in the cladding material is shown in Table 2. The Co-based powder particle size is 55~105 μm and the TaC powder particle size is 1~10 μm, as illustrated in the SEM micrographs in Figure 1. In preparing the experimeSEnts, QM3SP04L high-energy planetary ball mill was used to grind the ball for 5 hours to ensure that the powder is fully mixed.

Table 1. Chemical composition of Stellite X-40

Element	C	Cr	Ni	W	Co
Content(wt%)	0.90	25.38	10.84	7.53	Bal.

Table 2. The composition of composite powders for the laser cladding

Number	Mixtures composition (wt. %)
Coating 1	StelliteX-40
Coating 2	StelliteX-40 + 10%TaC
Coating 3	StelliteX-40 + 20%TaC
Coating 4	StelliteX-40 + 30%TaC

After the laser cladding processes, the test specimens were divided into small samples of 10mm×10mm×10mm using wire cutting, and the surfaces were polished. The material properties of the samples were examined using advanced technologies like X-Ray Diffraction (XRD), Optical Microscope (OM), Scanning Electron Microscope (SEM), and Energy Dispersive Spectrometer (EDS). The numerical and experimental results indicate that laser cladding on propeller blade has potential to improve the propeller performance significantly. Figure 8 illustrates the XRD patterns of laser cladding with different mass fractions of TaC enhancement phase. The Co-based coating without reinforcing phase is mainly composed of γ-Co and CoCr compounds. With the addition of the TaC reinforcing phase, new diffraction peaks of TaC were found at positions of 35.2°, 59.1° and 70.7°, respectively. Moreover, diffraction peaks of new Co3Ta intermetallic compounds were found at 50.4° and 74.5°. The discovery of Co3Ta compounds indicates that TaC decomposes into new Ta and C elements under the action of laser. Due to the strong affinity of Co and Ta, it is easy to generate new Co3Ta compounds in the cooling process of molten pool. There intermetallic compounds can effectively improve the hardness and wear resistance of coating, like the carbide reinforced phase in alloys. The appearance of new Cr3C2 carbides at the 50.5° and 74.9° positions indicates that the C element decomposed by TaC is combined with the Cr element. With the increase of TaC mass fraction, the peak value of γ-Co decreased, the peak value of TaC and Cr3C2 increased significantly, as well as the diffraction peak of CoCr at the position of 43.4° was replaced by the new Cr3C2. This is mainly because the binding force of C and Cr is greater than that of Co. Therefore, a large amount of Cr atoms preferentially combine with C atoms to form new Cr3C2 carbides during solidification of the molten pool. Cr3C2 has high hardness and corrosion resistance, and its uniform distribution with TaC in the coating can effectively improve the wear resistance and corrosion resistance of the coating.

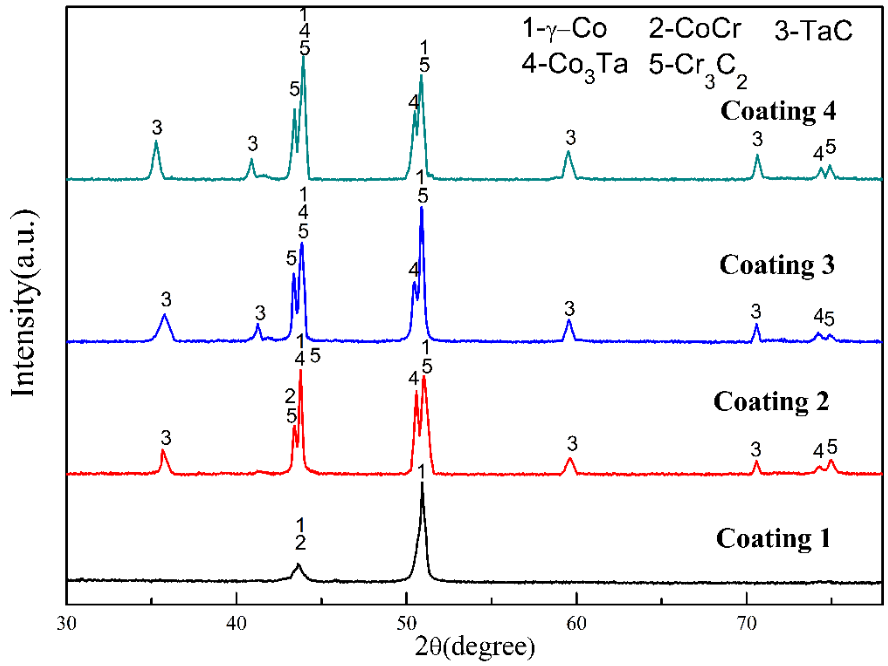

Fig.8 XRD patterns of cladding layers

Figure 9 shows the hardness distribution along the longitudinal direction of the laser cladding composite coating. The micro-hardness of the composite coating is obviously higher than that of the matrix. The micro-hardness distribution increases along the matrix, the transition zone and the coating. What's more, the hardness distribution on the coating is more uniform. The average hardness of the composite coatings is 594.2HV, 691.7HV, 771.7HV and 712.4HV, which are about 4.7-6.2 times of that of the matrix (125.1HV). According to the analysis of SEM, the main reason is that laser cladding has the characteristics of rapid heating and cooling, resulting in fine grain strengthening. In addition, the Co-based alloy contains a large number of Cr elements, which will also produce solution strengthening to improve the hardness of the coating. The hardness of the coating increases obviously with the increase of TaC content, which is due to the high hardness of TaC and the combination of C atoms decomposed by TaC and Cr atoms during laser scanning to form a new Cr_3C_2. The uniform distribution of TaC and Cr_3C_2 in the coating can effectively improve the hardness of the coating, and a large number of Ta atoms solidify in the molten pool, which can also be used as the core of heterogeneous nucleation to further refine grains and improve hardness. When the mass fraction of TaC is 30%, the hardness of the coating decreases and the hardness distribution fluctuates greatly. Combined with SEM analysis, when the content of TaC is too high, it is not enough to melt the coating during the melting process, which results in the larger particles in the coating and the coarsening of the structure. Dendritic structure is similar to that of coatings without reinforcement phase, which indicates that appropriate amount of TaC decomposition can obviously refine the grain size. Excessive amount of TaC will result in the failure of reinforcement phase to decompose and reduce the hardness of coatings, and the uneven distribution will lead to greater fluctuation of the hardness of coatings.

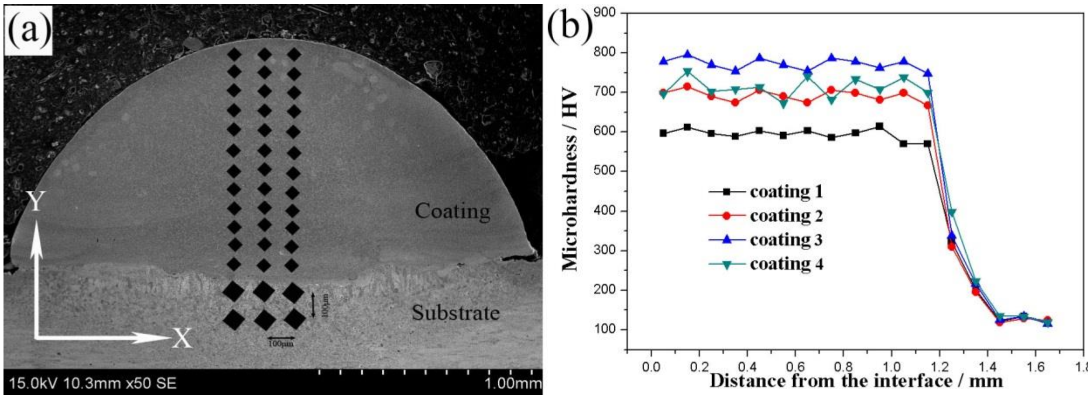

Fig.9 Microhardness distribution curves of laser cladding composite coatings

5 Concluding remarks

In this pre-study project, we aimed to improve a propeller's ice performance while keeping its open-water profile through implementing laser surface treatment on the propeller blades. Numerical analyses of laser cladding and grinding processes were carried out using FE method. The numerical simulations indicate that laser cladding improves the resistance of the marine propeller materials against repeated ice impact loads. Cladding experiments were conducted using TaC/Stellite X-40 Co-based composite cladding layers were. TaC reinforced Co-based composite coatings were successfully welded on the NAB substrate surface using laser cladding technology. It was observed that the cladded layer and the substrate are metallurgically bonded. It is also found that the coating layer improves the surface hardness significantly, which indicates that cladding treatment has the potential to improve the propeller performance.

The research results of the PROFFS project led to the following publications:

- Patel, S., & Bellary P., (2019). "Study on laser surface enhancement of marine propellers", Master thesis, report no. 2019/62, Chalmers University of Technology, Gothenburg, Sweden
- Li, Y., (2018). "Finite element simulation of the laser surface treatment process of a two-material propeller". Master thesis, report no. 2018/47, Chalmers University of Technology, Gothenburg, Sweden
- Li, Z., & Ringsberg, J.W., (2019). "Finite element simulations of the laser surface treatment process and cavitation loads of a two-material propeller", Presentation on the 8th International Conference on Computational Methods in Marine Engineering (Marine 2019), Gothenburg, Sweden, 13-15 May, 2019.