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DESIGN AND OPERATIONAL DIAGNOSTICS OF MARINE PROPELLERS MADE OF POLYMER MATERIALS

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ABSTRACT

There has been a rapidly growing interest in the use of composite and polymer materials for the construction of marine propellers for over 20 years. The main advantages of these materials are a reduction in the weight of the propeller, increased efficiency due to the hydroelasticity effect, a reduction of the hydroacoustic signature, and a cost reduction for serial production. This paper presents an overview of diagnostic methods that can be applied at the design level and during the operation of marine propellers made of polymeric materials. Non-invasive contact and non-contact-based diagnostic techniques for evaluating the technical state of the propeller are reviewed, and the advantages and disadvantages of qualitative and quantitative methods are identified. Operational diagnostic procedures for propellers are areessential for the safety of vessels at sea. Finally, the structure of a diagnostic system is proposed. It combined diagnosis process with the genesis of damage and the prognosis of the technical condition, i.e. production and in-service diagnostics.

Keywords: diagnostics, polymeric materials, propellers

INTRODUCTION

The production of propellers made of polymeric materials and their composites has four main advantages. Firstly, it may be more economically advantageous than the use of alternative materials [1]: bronze propellers require highly specialised experts to provide the required geometry during production, whereas moulding a propeller in a polymer material requires only the removal of excess polymer or resin, which is not a costly or expert task, and is technology dependent. The simplicity of production is a further factor supporting this criterion. For small boats, there is likely to be a need to manufacture a series of consecutively dimensioned propellers prepared to fit the corresponding power packs [2]. This approach also lowers costs, and means that production is fast and cheap. Another factor is the durability of the propeller, as a viable propeller made from isotropic material must have enough strength to withstand the operating load [3]. Tests of composite materials [3-5]adding up analysis of fatigue damage mechanisms by combining different techniques: optical microscopic and X-ray micro-tomography observations, temperature field measurement by infrared camera, and acoustic emission monitoring (AE subject to thermal conditioning and operation in water indicate that they have high strength properties, and are strong enough to withstand the operational loads on marine propellers. The third factor is the service life of the propeller when submerged in water. Research carried out at many centres [6, 7] has demonstrated the excellent properties of polymers as materials for submerged propellers. The last factor in favour of polymer propellers is their hydrodynamic advantages, as it is possible to design the necessary properties through the use of composites for propellers. In the case of isotropic materials, suitable selections can be made to improve their properties and efficiency.

Despite the use of composites and polymers being ideal for manufacturing propellers, there is still a need to diagnose them. In this paper, we consider only propellers made of isotropic polymer materials, and we show how to achieve the necessary physical properties of these materials to achieve results consistent with FEM models. Hazards are identified, and we present a proposal for a diagnosis system for use in the production and operation processes. Finally, we present a discussion on the applicability of the available diagnostic methods and highlight those that are suitable for application in the production of propellers, based on efficiency and economic factors.

METHODS OF MANUFACTURING ISOTROPIC PROPELLERS

In this section, we discuss the influence of material properties and manufacturing technology in terms of obtaining the desired geometry and operational properties of marine propellers made of polymer thermoplastic materials. An example of a modular propeller made with this technique is shown in Fig. 1.

The manufacturing technology used is inevitably related to the geometry and material of the propeller [9]. It is possible to find modular propellers with adjustable attack angles that are made as a monolith [10]. Tadashi researched and analysed the elastic deformation of five-wing propellers made of polyamide, aluminium and epoxy-carbon composites, and reported that the torque and driving force of propellers made of polymeric materials were comparable to those of aluminium. However, polymeric propellers deform elastically, resulting in higher efficiency and reduced cavitations [11].

Fig. 1. A flexible modular propeller

The blades of the propeller may be made of polyamide 66 and polyacetal. These are thermoplastic, isotropic, and deformable materials, and due to their properties, they offer an excellent alternative to composite, aluminium, or other types of propellers.

Table 1 shows the properties of the materials analysed here, which represent the results of our research. Tests were carried out on samples in the conditioned state (4 h at 80°C in water, and then cooling to room temperature). Their different properties were the result of modifications and the manufacturing technology used for samples (injection moulding). The tensile strength was determined following ISO 527 (sample type A), density following ISO 1183, and absorption following ISO 62.

The literature contains many solutions for producing propellers from isotropic polymer materials, including injection moulding, CNC, and 3D printing. Each of these methods has certain advantages and limitations; for example, propellers produced by 3D printing (the FDM method) experience problems with heterogeneity, resulting from the melting of the filament, and air blistering, which affects the corrosion resistance. CNC, like 3D printing, is time-consuming, and compared to injection moulding technology, the production time for detailed components is much longer. Injection moulding is expensive and time-consuming at the production start-up stage, but is profitable for high-volume production. It allows for the manufacture of details with a homogeneous structure, excellent properties, and a smooth surface, and the properties of each detail can be reliably controlled. The problem, however, is the cost and time of manufacturing the tool. An adequately designed form considers the material's properties through the use of a mould flow index, which is essential to account for the flow path, shrinkage, water absorption, material modification, filling degree, etc. [12].

Tab. 1. Properties of isotropic thermoplastic polymer materials

Material	Young's modulus [MPa]	Breaking stress [MPa]	Breaking strain [%]	Density (dry) [g/cm³]	Water absorption [%]
Zytel 153 HSL NC010 (PA66)	1266	55.82	296.66	1.06	3.2
Zytel 135 F NC010 (PA66)	2294	60.44	5.63	1.139	4.1
Zytel 101 BKB080 (PA66)	1736.38	48.2	167.76	1.14	2.8
Delrin 100P NC010 (POM)	2514.8	65.44	76.01	1.42	1.8
Nevimid 6D Natural (PA 6)	1634.06	31.52	124.65	1.135	2.1
Alphalon 27C (PA 6)	820	40.9	230.5	1.13	2.8
Tarnamid A3S NAT (PA66)	1180	47.1	273.5	1.15	1.7
Technyl C 202TR C (PA6)				1.138	1.41
Technyl A205F natural (PA66)	1714.	55.74	56.27	1.145	1.362
Tanform 411 (POM)	2711.92	62.66	57.367	1.408	0.74

The basis for obtaining a detailed component with the necessary properties is a properly designed and stable process, which is influenced by many factors characteristic of the material (such as the degree of drying, flow index, shrinkage, processing temperatures, viscosity, orientability), the technology used (machine, mould) and the environmental conditions [13].

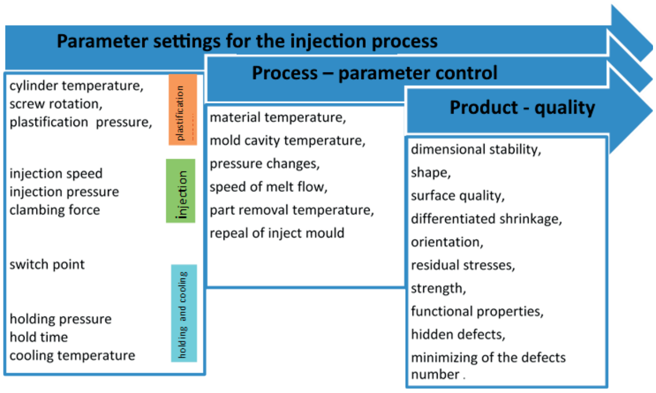

Fig. 2. Influence of parameters on the material properties [13]

In this research, we assume that the injection process is carried out on a DEMAG Extra 80-430 injection moulding machine, using a single-cavity cold-runner mould. The mould will be designed in the Siemens NX. Simulations of the injection process will be carried out in the Autodesk Moldflow. The propeller blades are made of polyamide 66 (Technyl A205F natural (PA66) and polyacetal (Tanform 411). Before the process, the materials are dried (at 80°C for 4 h) to ensure the quality of the part. At equilibrium, the moisture content (without polycondensation and RV dip) is about 0.12% at a melt temperature of 295°C.

If the content of water by weight in the granulate is lower than 0.20%, the rates of hydrolysis and polycondensation are so low under normal conditions that these phenomena have practically no effect on the properties of the formed component. Hence, drying of the input material is required, as moisture directly impacts the forming process, the mechanical properties, the viscosity of the melted material, and the appearance of the manufactured parts. At a temperature exceeding the melting point, water reacts with the polyamides. This causes a reduction in the molecular weight and thus a deterioration in the properties of the compacts rheological hardening of the molten mass, which can lead to problems such as the formation of overspray. It may also be difficult to keep the dimensions of the details within the tolerance limits. The absorbed water can later evaporate, resulting in craters and internal bubbles in the product. The negative effect of moisture on the melted polyamides is exacerbated by a long residence time and/or a high temperature of the molten material (>315°C). This is due to the decrease in molecular weight, which is reflected in the relative viscosity of the liquid. In this case, it is advisable to reduce the water content accordingly. The properties of polyacetal are not dependent on water absorption. The parameters used in the injection moulding process are listed in Table 2.

Tab. 2. Injection moulding parameters

Parameters	Technyl A205F natural (PA66)	Tanform 411
Temperature [°C]	220–260	180–210
Molding pressure [MPa]	140	120
Cooling time [s]	65	65
Mould temperature [°C]	70	80

Typical errors in the injection moulding process include the case where the mould cavity is not filled (insufficient injection volume), flashes, silvering, burns (the Diesel effect), blisters, flow lines, weld lines, cracks, warpage, and deformation forming a sink in the surface of a moulded product. These disadvantages can be minimised or eliminated by appropriate choices of the injection moulding parameters. In addition, surface defects can have a significant effect on cavitation erosion. A further important factor is the degree of crystallinity of the materials, which directly affects the operational properties, and the stiffness of the material is of particular importance for the acoustic characteristics.

DIAGNOSIS METHODS FOR POLYMER AND COMPOSITE MATERIALS

Polymer materials are used in a variety of machining and injection moulding processes. Unlike composites, polymeric materials are usually isotropic, although this depends on many factors [11]. Polymers are widely used in the marine industry to resist corrosion and aggressive chemical components. Their main advantage is that after conditioning, they can operate under large temperature fluctuations, which do not affect their properties. This is essential, as it means that polymer propeller blades will not expand, contract or change their geometry due to environmental influences, which is important for the hydrodynamic performance of the propeller. The production susceptibility of the material is a further advantage of polymeric materials over metals. These materials can be formed into any desired shape, which is vital for achieving the geometry of the propellers, and allows for a reduction in the total costs of manufacture and operation. As mentioned above, however, isotropic materials have certain drawbacks compared to other materials. The higher initial cost of producing polymer blades or propellers compared to metals is perhaps the most significant disadvantage. This cost mainly arises from the need to make a precise, long-lasting mould for the manufacturing process. Other disadvantages are changes in the physical properties after the conditioning process and deviations in the propeller geometry due to thermal shrinkage, which can lead to costly and difficult damage checks in the production phase.

It can be seen that the use of polymeric materials in the manufacturing of propellers presents some challenges in terms of engineering and maintenance. This makes it necessary to inspect and diagnose damage after forming the propeller and after its operation in seawater. Due to the potential failure mechanisms and the technical possibilities of identifying these failures, diagnostic processes for polymer products for marine propellers have been divided into two types: production and operational [14]X-rays computed tomography (XR-CT. In this work, a diagnostics methodology was considered that involved a division into non-destructive assessment (NDE) and non-destructive testing (NDT) of polymer propellers [15]fibre reinforced plastics have found a broad application in chemical apparatus and plantconstruction. Because of improved standards for safety, reliability and cost effectiveness of such composite components, numerous technical challenges arise for the producers of pressure vessels, tanks, reactors and pipe element systems. In this context, a multitude of problems appear during recurring acceptance inspections and equipment condition monitoring using non-destructive test methods. Promising advantages arise from novel monitoring concepts based on semi-active or even absolutely autarkic wireless sensor networks with so-called "sleeping sensors" as key function units with remote enquiry. These autonomoussensor-based monitoring modules are directly integrated into the composite and start recording signals not before a defined threshold is increased. This article discusses the scientific-technical issues that arise during the development of such intelligent damage monitoring systems. This includes the sensor network design, the sensor integration during manufacturing and the correlation between the relevant damage mechanisms and the sensor signals. Exemplary, sensor networks are integrated in GFPR composites. These composites have been tested in order to demonstrate the modes of operation of the sensor techniques and theircapability to detect the relevant damage mechanisms.","collection-title":"11th International Conference on the Mechanical Behavior of Materials (ICM11. These activities involve identifying and characterising damage to the surface and interior of components without damaging them: NDE refers to the process of non-invasive evaluation and control of components against in-service standards [16], whereas NDT techniques involve sample testing methods used in a production quality control system [13]. At the beginning of the 21st century, the division of the aforementioned diagnostic methods was common and acceptable. However, the development of diagnostic procedures and techniques meant that both methods began to be used in the production and in-service testing of polymer materials.

For reasons of strength, polymer propellers are made in two ways:

1. Uniform injection of the ring/blades assembly, which is attached to the hub by a conical interference and a nut;
2. Making straight blades, fixing them to a hub made of bronze or other metal, and then assembling them on the propeller shaft.

This means that the diagnostics process may relate to either a ring with blades or a single blade of the propeller.

The types of damage to marine propeller elements made of polymeric materials are listed in Table 3 [17]. It is challenging to select appropriate diagnostic techniques for a specific purpose, such as for a polymer propeller. Numerous diagnostics methods have been developed for polymer structures based on different principles, and these can be categorised into five groups:

1. Visual checks with the human eye, mainly of the surface;
2. Acoustic wave-based techniques (AE, nonlinear acoustics and ultrasonic waves);
3. Optical techniques such as infra-red testing (IRT), THz testing, shearography and DIC;
4. Imaging-based techniques such as X-ray/neutron radiography/tomography and micro-tomography;
5. Electromagnetic field-based techniques such as eddy-current testing, remote field testing, magnetic particle inspection and magnetic flux leakage testing.

Tab. 3. Manufacturing and in-service flaws in a polymer propeller structure with their potential scale [18]

	Scale of damage/failure	
	Micro scale	**Macro scale**
Manufacturing-induced flaws	Phase separation	Chain ends
	Micro-voids	Weak entanglement
	Filler particles (low interfacial adhesion)	Overstressed bonds
	Crystallised domain	Weak cross-linking
	Spherulite boundary	Intra-lamellar defects
	Inter-lamellar (amorphous region)	
In-service failure/damage	Deteriorative effects caused by oxidation, thermal exposure or UV radiation	Creep (cold flow), i.e. the tendency to move slowly or deform permanently under the influence of persistent mechanical stresses acting on the propeller blade
	Changes in the micro-structural scale caused by static and dynamic loading	Breaking or twisting due to overload
	Deteriorative effects of water saturation	Surface wear due to friction with impurities in the water (impurities)
	Changes in roughness due to the action of sea water	Ceiling temperature

Most diagnostic methods require perfect contact between the gauge and the testing surface to avoid errors or disturbances. Contact methods include ultrasonic, eddy current, magnetic, electromagnetic and penetrant testing. Non-contact methods speed up the data collection process, and include transmission ultrasonics, radiography testing, thermography, shearography, and visual inspection. Optical methods include thermography, holography and shearography, which are primarily non-contact techniques. Based on a review of these diagnostic methods, they can be categorised, as shown in Table 4 [19].

Tab. 4. Contact and non-contact diagnostics methods [16]

Contact methods	Non-contact methods
Traditional ultrasonic testing	Through transmission ultrasonic testing
Eddy current testing	Radiography testing
Magnetic testing	Thermography
Electromagnetic	Infrared testing
Penetrant testing	Holography
Liquid penetrant	Shearography
—	Visual inspection

PROPOSED DIAGNOSIS METHOD FOR POLYMER PROPELLERS

As previously mentioned, damage to propellers and defects may occur in the production or in-service phases. Due to the difficulty of access to the tested object, and to make the cost of diagnosis more realistic (compared to replacement with a new propeller), it was proposed that the effectiveness and financial analyses justify choosen technical diagnostics method. This method can be used for the most common defects, and does not require the ship's propulsion system to be taken out of service.

PRODUCTION DIAGNOSTICS PHASE

Experience of CNC machining and moulding of polymer propeller blades indicates that the most common manufacturing defects are as follows:

- Exceeding the permissible shape errors connected with thermal crusting;
- Changes in physical properties resulting from the conditioning of the material;
- Heterogeneity of the material due to micro-scale failures;
- Changes to the structure of the material in the form of macro-scale failures.

In view of the effectiveness of defect detection and the cost of using diagnostic methods, it is recommended to use a three-step diagnostic process, as follows:

1. A visual check with the human eye, mainly of the surface. This is quick, economically viable and flexible, although the drawbacks of this method are significant. Visual analysis is the main procedure for the monitoring of surface imperfections based on acceptance/rejection criteria during the production of blades.
2. IRT is an effective method of detecting and processing an object's infrared energy emissions by measuring and mapping thermal decomposition. The thermal conductivity of the polymer changes in the presence of defects, which can be detected using thermal imaging cameras. Thermographic testing is effective for thin parts such as propeller blades. The flaws do not move deeper due to the low thickness. It means that heat fluctuations in the defective area are visible (see Figure 3).
3. 3D scanning tests and validation of the geometry of a virtual blade. These tests require the preparation of the measurement path and wing mapping (see Fig. 4). Thermal skins and injection imperfections can result in errors in the blade geometry. However, such tests indicate the size of the errors and should not be omitted from the initial phase of blade manufacture (see Fig. 5).

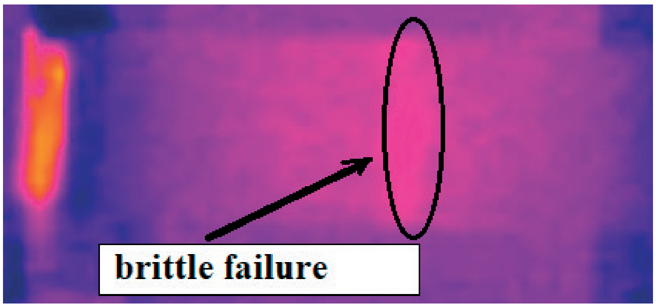

Fig. 3. Thermographic image of a specimen during tensile testing after fracture [20]

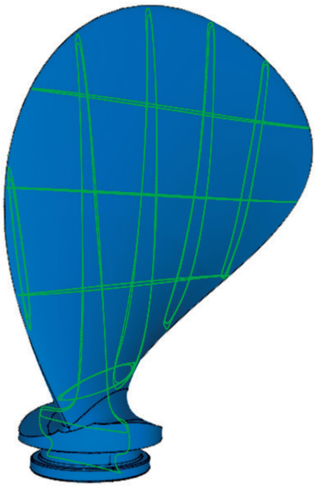

Fig. 4. Measurement path on the surface of the blade

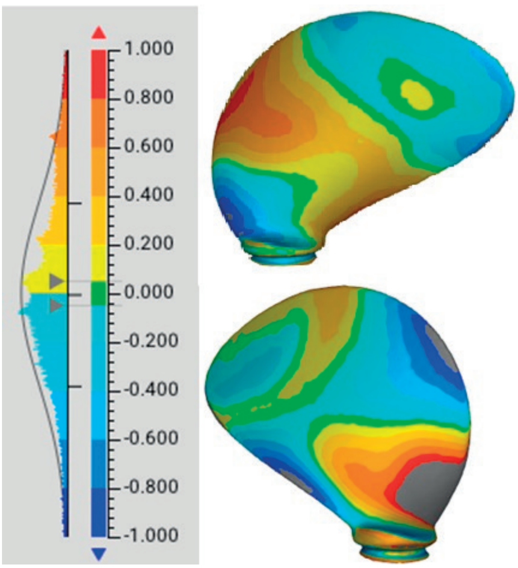

Fig. 5. Map of the deviations between the reference model of the blade and the 3D scan in-service diagnostics phase

Polymer propellers can be used for small recreational boats and medium-sized vessels. For small leisure boats, the use of diagnostic systems is impractical for economic reasons; these crafts operate seasonally, and the cost of the diagnostic system would be comparable to or higher than the cost of the entire shaft line with the propeller. For commercial vessels, the diagnostic strategy should be practical and cheap to purchase and use. According to this diagnostics phase has been divided into online and offline procedures to meet.

An online diagnostics procedure can use sound pressure level (SPL) measurements in the area adjacent to the propeller. For example, the attachment of the hydrophone on the underwater part of the hull should be located close to the propeller (Fig. 6). During Sea Acceptance Tests (SATs), measurements should be made on a new, technically efficient propulsion system. They shoul be conducted for specific load conditions to obtain pattern spectra of the SPL in the range of the bandwidth filter for following loads.

Fig. 6 Attachment of the hydrophone on the underwater part of the hull

The sound pressure level (SPL) in a specified frequency band is defined as follows [21]

$$SPL = 10\log_{10}\frac{p_{RMS}^2}{p_{ref}^2} \quad or \quad 20\log_{10}\frac{p_{RMS}}{p_{ref}} \tag{1}$$

When analysing and reporting the absolute values of acoustic levels in decibels, it has been recommended that the following principles be adopted [21–23]:

- State the physical parameter clearly;
- State any averaging time clearly;
- State the frequency of the diagnostic bandwidth clearly (for propeller type and load);
- State any frequency weighting.

This type of diagnostic approach is indirect. It assumes that the defects or damage visible in various frequency ranges will affect the hydroacoustic characteristics of the propeller over the entire range of its load. Such diagnostic procedure means that the defects in the propeller material will be detected at an advanced degree of damage. However, from a practical point of view, the detection of blade flaws in either the initial or final stages of propeller failure has the same result, i.e. replacement of the propeller. An example of a spectrum after the application of the medium-pass filter is shown in Fig. 7.

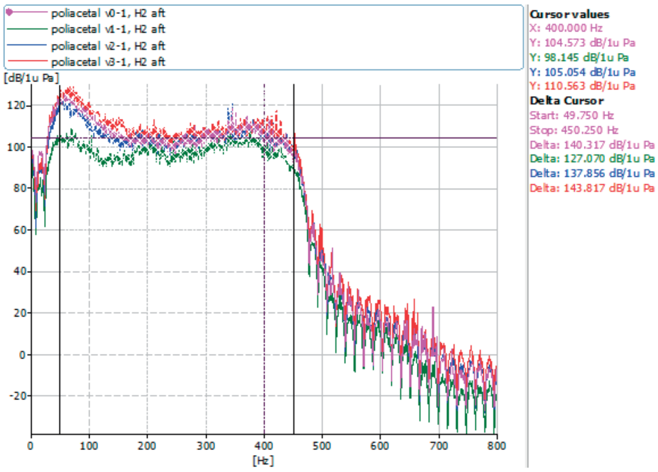

Fig. 7. Example of an SPL spectrum with a medium-pass filter for a test of a polyacetal propeller measured, v0-1 = 0 m/s(bollard pull), v1-1 = 1 m/s, v2-1 = 2 m/s, v3-1 = 3 m/s.

DISCUSSION

The proposed production and in-service diagnostics methodology presented in this paper represents a compromise between the expectation of safe operation and economic considerations. The growing interest in cheap propellers made of polymer materials results in a need to maintain the propellers to ensure high quality and longevity. Propellers diagnostic during production and in-service should be a natural process [25]. As described in the second section, NDE and NDT of polymer propellers are intended for products made of isotropic polymers and composites. Depending on the future use of the product, its use may be limited by the high diagnostic costs. A significant proportion of existing diagnostic methods are intended for products used in the space and aviation industries and those that require resistance to high pressures, such as LNG tank containers. The design of polymer propellers is conditioned by high safety factors, as flaws may result from production errors or contact of the propeller with hard objects floating in the water, such as pieces of ice or wood. The development of cheap production diagnostics and in-service measurement is therefore important to meet the needs of the maritime market.

CONCLUSIONS

The results of our research, analyses, and literature review confirm the benefits of using a two-stage diagnostic process for polymer propellers. The main advantages of this approach are the effectiveness of these diagnostic methods and their cost-effectiveness.

Research in the production phase with the use of 3D scanning in the initial production phase ensures that the appropriate injection technology can be selected for various materials. However, it should be noted that for the same form, a change from one material to another causes deviations in the final geometry of the propellers due to thermal contractions. A similar phenomenon occurs after conditioning of the propeller, meaning that another 3D scan is also needed after this stage.

Damage to marine propellers is common, and applies to all propellers regardless of the material from which they are made. The proposed SPL measurement technique, in its basic version, may reveal secondary effects from damage or fracture of the propeller. The proposed method also allows for the identification of cavitations in the higher frequency range, which can complement the basic version of the diagnostic system. Hence, in-service measurement with SPL is a highly efficient diagnostic tool [26].

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