NAVAL PROPELLERS RECONDITIONING BY FRICTION STIR WELDING - FSW

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ABSTRACT

The naval propeller is subjected to high cycling fatigue loadings and shocks. Besides, working in corrosive medium, cracks and, finally, fractures could be developed in different regions of the propeller. Because the zones of the propeller don't work in similar conditions, the damage is not the same in all regions.

The paper presents considerations about alloys for naval propellers, working conditions, wear and failure, reconditioning and testing of the naval propellers.

KEYWORDS: naval propellers, reconditioning, FSW

1. ALLOYS USED FOR NAVAL PROPELLERS

Table 1 presents the chemical composition of copper alloys for naval propellers, recommended by Germanischer Lloyd (CU1, CU2, CU3 and CU4), and A-1123 and A-1124 used for naval propellers reconditioning by Robotics and Welding department.

Naval propellers of CuNiAl alloy have to be repaired starting from casting to working phase.

Table 1. Alloys used for naval propellers

ALLOY	CHEMICAL COMPOSITION, [%]			
	Cu	**Sn**	Zn	Pb
	Ni	Fe	**Al**	**Mn**
CU1	52-62	0.1-1.5	35-40	Max 0.5
Manganese Bronze	Max 1.0	0.5-2.5	0.5-3.0	0.5-4.0
CU2	50-57	0.1-1.5	33-38	Max 0.5
Nickel - Manganese Bronze	2.5-8.0	0.5-2.5	0.5-2.0	1.0-4.0
CU3	77-82	Max 0.1	Max 1.0	Max 0.03
Nickel - Aluminium Bronze	3.3-6.0	2.0-6.0	7.0-11.0	0.5-4.0
CU4	70-80	Max 1.0	Max 6.0	Max 0.05
Manganese - Aluminium Bronze	1.5-3.0	2.0-5.0	6.5-9.0	8.0-20.0
A-1123	79.7	0.24	-	0.189
	4.82	4.86	9.33	0.5
A-1124	80.0	0.28	-	0.23
	4.56	4.42	9.67	0.4

In the casting phase of the naval propellers casting defects can occur and have to be repaired before mechanical working applying Friction Stir Processing (FSP) procedure.

In the mechanical working phases hidden defects could occur which have to be repaired by welding. The both defects categories are developed in all regions of the naval propellers including their blades and block. In the working phase the defects - such as cracks, pinches, fracture or bends - are developed in the propeller blades, top areas and entering edge caused by shocks produced during rotation and stationary. On the march, when bends or fractures could occur, shipboard anchorage and trim by the bow is required. After its trim by the bow, the opposite blades are symmetrically cut for a crude balancing.

Excepting the bends and large fractures, the rest of defects which occurs on the march can be repaired by welding procedure after the shipboard is down by the bow. Regardless of defect type, the reconditioning has to be performed only by authorized companies.

2. NAVAL PROPELLER: WORKING CONDITIONS, WEAR AND FAILURE

The naval propeller is subjected to high cycling fatigue loadings and shocks. Besides, working in corrosive medium, cracks and, finally, fractures could be developed in different regions of the propeller. Because the zones of the propeller do not work in similar conditions, the damage is not the same in all regions.

Naval propeller block: Important stresses occur in this area, because of the propeller assembling on the propeller shaft. The internal region of the block is not in contact with sea water and the corrosion danger doesn't occur. The external surface is understressed, peripheral speed is low in this area and, therefore, the erosion phenomenon is reduced.

Blades: The blades, excepting their edges, are subjected to important cycling fatigue loadings. The sea water action is reduced in these regions, due to the rotation low speed. Over distance of 0.4R (where R is the radius of the propeller) the tensile loads decrease. The propellers edges are subjected to low tensile loads, with reduced cyclic variations, but are strongly exposed to the sea water action. When blades flutters are developed, the edges are subjected to high variations of stresses, especially for 0.5R and 0.7R values range. The suction side of the blades is less mechanically stressed and exposed to the cavitation phenomenon. If the propeller is imobil or has a low rotative speed in the sea water the bronze propellers corrosion is of 0.05 mm/year. The wear value is 3-4 times higher to the blades extremities and, therefore, after few working months, the bright disappears and the roughness increases in these areas. Besides, because of the corrosion a local wear, consisting of pinches (pitting phenomenon), is developed on the blades edges and the propeller performance characteristics are serious affected. After docking, the pitches have to be polished until the smoothing of the cavitations edges. Sometimes special putties are used but this is not a durable solution.

In certain areas from the aspiration side of the blades, the sea water doesn't make contact with the blade surface. Therefore, blankness occurs and steams balls are resolved. Implosion of these balls develops an impact energy which generates the erosion of the material. The cavitation phenomenon can't be prevented. When the reconditioning procedures are improper, the local defects, such as the cracks, rest in the material. In the working phases, the cracks – especially if they are located in the pressure side of the blade - promote the tension cracking corrosion and, finally, fatigue fracture of the blade. The fatigue fracture can occur also if there are residual stresses from the casting or reconditioning phases. The fracture is characterized by two different regions:

- the grain-refining region which, usually, begins from a small defect located on the pressure surface and corresponds to the fissured area;
- the grain-coarsening region corresponds to the broken section.

It is recommended to identify the surface defects, especially of the residual fissures from the reconditioned regions, using liquid penetrant examination (ferric chloride in case of bronze propellers). The breaking up/bending of the blades occurs also because of the navigation accidents (wrecks, impacts with objects, etc.). In case of breaking up, the sterntube shaft must be examinate to check its state.

Taking account of nuisance value of the defects, the propeller surface is divided into three regions (A, B, C), as the fig. 1 shows.

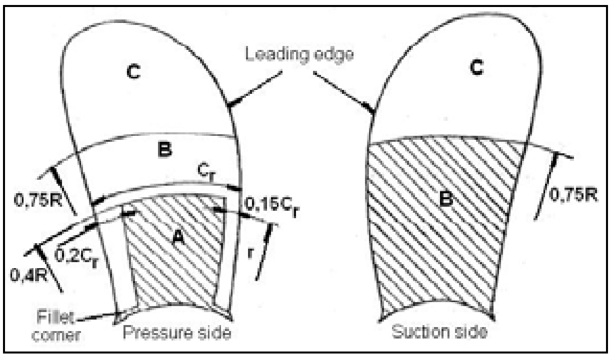

Fig.1. Severity regions of propeller: R- propeller radius; Cr- string length corresponding to radius r

3. NAVAL PROPELLER RECONDITIONING

The reconditioning procedure can be applied in case of slight defects detected by visual inspection and liquid penetrant examination. Adjacent defects which cause the welds interaction are considered a continuous single defect. The defects reconditioning depends on their size and location.

Region A: The reconditioning by welding is not allowed. The defects having smaller depths than 2 mm or t/50 mm (where t is the minimum thickness according to RNR - The Romanian Naval Authority - rules) can be eliminated by polish method. The isolated defects very small, such as pores with diameter less 1 mm, are not cut out.

Region B: The defects having smaller depths than 2 mm or t/50 mm can be eliminated only by polish method. The defects with higher depth, but not higher than t/3 mm, can be repaired by welding method. When the depth is higher than t/3 mm, the reconditioning can be made only with the approval of RNR

Region C: The reconditioning by welding is allowed. The repairs made on the naval propeller block surface and especially on the propeller blades must be carefully performed in order to avoid thermal stresses which cause the cracks occurrence.

In the regions B and C the reconditioning by welding can be applied when:

- each surface repaired is up to 60 mm^2 or 0,6 %'S (where S is the blade surface);
- the total surface of repairs doesn't exceed 200 cm^2 or 2%-S;
- in the region B , from the pressure side, the total surface is not higher than 100 cm^2 or 0,8 %'S.

The welding procedures admitted to be applied for the naval propellers reconditioning are SMAW, MIG and TIG which assure a fast and focused melting. The reconditioning by welding is performed by welders authorized by RNR. After the reconditioning, the workpieces are subjected to the tempering treatment approved by RNR. The heating time is set up in order to assure a uniform temperature, a complete penetration of the workpiece and depends on the alloy type, temperature treatment and workpiece dimensions. The cooling speed must be low (up to 50°C/h).

In the region C, marginal cracks can be developed as result of hydrostatic pressure action, fatigue loading etc as fig. 2 shows.

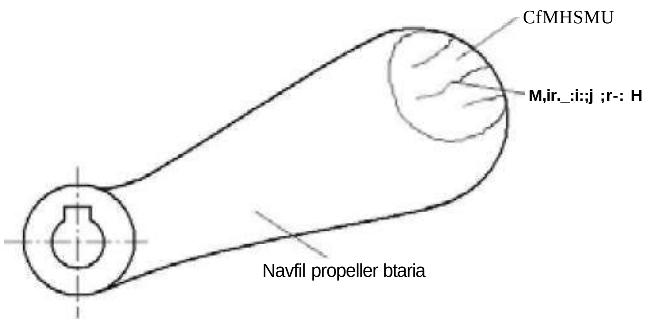

Fig.2. Naval propeller blade: marginal cracks

A more advantageous procedure which can be applied for the naval propeller reconditioning is FSW (friction stir welding). Friction-stir welding (FSW) is a solid-state joining process (meaning the metal is not melted during the process) and is used for applications where the original metal characteristics must remain unchanged as far as possible.

This process is primarily used on aluminium, and most often on large workpieces which cannot be easily heat treated post weld to recover temper characteristics. It was invented and experimentally proven by Wayne Thomas and a team of his colleagues at The Welding Institute UK in December 1991.

A number of potential advantages of FSW over conventional fusion-welding processes have been identified [8]:

- Good mechanical properties of the welds.
- Improved safety due to the absence of toxic fumes or the spatter of molten material.
- No consumables - conventional steel tools can weld over 1000m of aluminium and no filler or gas shield is required for aluminium.
- Easily automated on simple milling machines - lower setup costs and less training.
- Can operate in all positions (horizontal, vertical, etc), as there is no weld pool.
- Generally good weld appearance and minimal thickness under/over-matching, thus reducing the need for expensive machining after welding.
- Low environmental impact.

In FSW, a cylindrical-shouldered tool, with a profiled threaded/unthreaded probe (nib or pin) is rotated at a constant speed and fed at a constant traverse rate. The length of the pin is slightly less than the weld depth required and the tool shoulder should be in intimate contact with the work surface.

Frictional heat is generated between the wear-resistant welding tool shoulder and nib, and the material of the workpieces. This heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without reaching the melting point (hence cited a solid-state process), allowing the traversing of the tool along the weld line in a plasticized tubular shaft of metal. As the pin is moved in the direction of welding, the leading face of the pin, assisted by a special pin profile, forces plasticized material to the back of the pin while applying a substantial forging force to consolidate the weld metal.

The welding of the material is facilitated by severe plastic deformation in the solid state, involving dynamic recrystallization of the base material.

The solid-state nature of the FSW process, combined with its unusual tool and asymmetric nature, results in a highly characteristic microstructure. While some regions are common to all forms of welding some are unique to the technique.

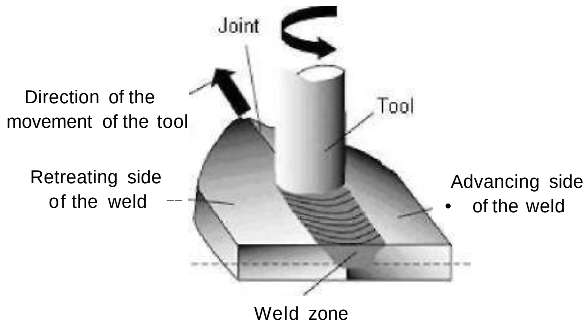

Fig.3. The progress of the tool through the joint

While the terminology is varied the following is representative of the consensus.

- The *stir zone* (also nugget, dynamically recrystallised zone) is a region of heavily deformed material that roughly corresponds to the location of the pin during welding. The grains within the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material . A unique feature of the stir zone is the common occurrence of several concentric rings which has been referred to as an 'onion-ring' structure. The precise origin of these rings has not been firmly established, although variations in particle number density, grain size and texture have all been suggested.
- *The flow arm* is on the upper surface of the weld and consists of material that is dragged by the shoulder from the retreating side of the weld, around the rear of the tool, and deposited on the advancing side.
- The *thermo-mechanically affected zone* (TMAZ) occurs on either side of the stir zone. In this region the strain and temperature are lower and the effect of welding on the microstructure is correspondingly smaller. Unlike the stir zone the microstructure is recognizably that of the parent material, albeit significantly deformed and rotated. Although the term TMAZ technically refers to the entire deformed region it is often used to describe any region not already covered by the terms stir zone and flow arm.
- The heat-affected zone (HAZ) is common to all welding processes. As indicated by the name, this region is subjected to a thermal cycle but is not deformed during welding. The temperatures are lower than those in the TMAZ but may still have a significant effect if the microstructure is thermally unstable. In fact, in age-hardened aluminium alloys this region commonly exhibits the poorest mechanical properties.

There are two tool speeds to be considered in friction-stir welding; how fast the tool rotates and how quickly it traverses the interface. These two parameters have considerable importance and must be chosen with care to ensure a successful and efficient welding cycle. The relationship between the welding speeds and the heat input during welding is complex but, in general, it can be said that increasing the rotation speed or decreasing the traverse speed will result in a hotter weld. In order to produce a successful weld it is necessary that the material surrounding the tool is hot enough to enable the extensive plastic flow required and minimise the forces acting on the tool. If the material is too cool then voids or other flaws may be present in the stir zone and in extreme cases the tool may break.

At the other end of the scale excessively high heat input may be detrimental to the final properties of the weld. Theoretically, this could even result in defects due to the liquation of low-melting-point phases (similar to liquation cracking in fusion welds). These competing demands lead into the concept of a "processing window": the range of processing parameters that will produce a good quality weld. Within this window the resulting weld will have a sufficiently high heat input to ensure adequate material plasticity but not so high that the weld properties are excessively reduced.

For any welding process it is, in general, desirable to increase the travel speed and minimise the heat input as this will increase productivity and possibly reduce the impact of welding on the mechanical properties of the weld. At the same time it is necessary to ensure that the temperature around the tool is sufficiently high to permit adequate material flow and prevent flaws or tool fracture.

When the traverse speed is increased, for a given heat input, there is less time for heat to conduct ahead of the tool and the thermal gradients are larger. At some point the speed will be so high that the material ahead of the tool will be too cold and the flow stress too high, to permit adequate material movement, resulting in flaws or tool fracture. If the 'hot zone' is too large then there is scope to increase the traverse speed and hence productivity.

The welding cycle can be split into several stages during which the heat flow and thermal profile will be different :

- *Dwell.* The material is preheated by a stationary, rotating tool in order to achieve a sufficient temperature ahead of the tool to allow the traverse. This period may also include the plunge of the tool into the workpiece.
- *Transient heating.* When the tool begins to move there will be a transient period where the heat production and temperature around the tool will alter in a complex manner until an essentially steady-state is reached.
- *Pseudo steady-state.* Although fluctuations in heat generation will occur the thermal field around the tool remains effectively constant, at least on the macroscopic scale.
- *Post steady-state.* Near the end of the weld heat may 'reflect' from the end of the plate leading to additional heating around the tool.

Heat generation during friction-stir welding arises from two main sources: friction at the surface of the tool and the deformation of the material around the tool . The heat generation is often assumed to occur predominantly under the shoulder, due to its greater surface area, and to be equal to the power required to overcome the contact forces between the tool and the workpiece.

Figure 4 shows the principle of reconditioning by FSW of the marginal cracks developed in the naval propellers.

In the fig. 5 is presented the CuNiAl bronze used for naval propellers when FSW procedure is applied. Microstructure refining and, finally, strength and ductility are improved in case of naval propellers reconditioning by FSW.

4. NAVAL PROPELLER TESTING

For the naval propellers testing, the most suitable methods are the following:

- **Visual examination** of the whole surface of the workpiece;
- **Liquid penetrant testing:** In case of new components, zone A must be tested using liquid penetrant method. In case of reconditioning, wherever is made, liquid penetrant procedure must be applied both after defect elimination and after reparation execution;
- **Ultrasonic testing:** If internal defects development is presumed, ultrasonic testing must be applied;
- **Radiographic inspection:** Internal defects can be discovered also by radiographic examination, using proper radiations sources in accordance with the workpiece thickness.

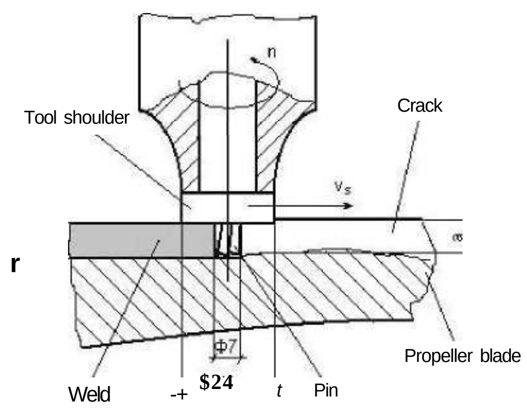

Fig.4. Reconditioning of naval propellers by FSW procedure

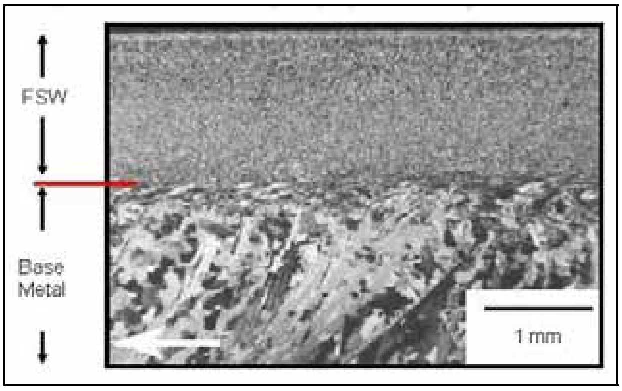

Fig.5. Microstructure refining by FSW procedure in case of CuNiAl bronze

5. CONCLUSIONS

- The naval propeller is subjected to high cycling fatigue loadings and shocks. Besides, working in corrosive medium, cracks and, finally, fractures could be developed in different regions of the propeller.
- Because the zones of the propeller don't work in similar conditions, the damage is not the same in all regions.
- A more advantageous procedure which can be applied for the naval propeller reconditioning is FSW (friction stir welding). Friction-stir welding (FSW) is a solid-state joining process (meaning the metal is not melted during the process) and is used for applications where the original metal characteristics must remain unchanged as far as possible.
- A number of potential advantages of FSW over conventional fusion-welding processes have been identified :
  - Good mechanical properties of the welds.
  - Improved safety due to the absence of toxic fumes or the spatter of molten material.
  - No consumables - conventional steel tools can weld over 1000m of aluminium and no filler or gas shield is required for aluminium.
  - Easily automated on simple milling machines - lower setup costs and less training.
  - Can operate in all positions (horizontal, vertical, etc), as there is no weld pool.
  - Generally good weld appearance and minimal thickness under/over-matching, thus reducing the need for expensive machining after welding.
  - Low environmental impact.

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