# Disposal and Recycling of HSC Materials

Manejo y reciclaje de materiales HSC

Henning Gramann[a],
Reinhard Krapp,
Volker Bertram

## Abstract

The introduction gives an overview of current IMO activities concerning the disposal of ships at the end of their life-cycle and an overview of composite materials applications in ships. After a brief discussion of relatively unproblematic aluminum alloys, the article focuses on problems for composite materials. There is little experience for end of life treatment of composites in general and in the shipbuilding industry in particular. New legislation might regulate handling and disposal of these materials even further. The article identifies existing solutions as well as open questions.

**Key words:** Environment, recycling, composite, high-speed craft

## Resumen

La introducción presenta un panorama de las actividades de la IMO relacionadas con el manejo de buques al final de su vida útil y de las aplicaciones de materiales compuestos en embarcaciones. Tras una breve discusión acerca de las aleaciones de aluminio que no presenta gran problema, el trabajo se enfoca en los problemas que presentan los materiales compuestos. Existe poca experiencia con el manejo de materiales compuestos al término de su vida útil en general y en la industria naval en particular. El manejo y eliminación de estos materiales podría ser regulado aún más por nuevas normas. Este artículo identifica las soluciones existentes así como preguntas actualmente sin respuesta.

**Palabras claves:** Medio ambiente, reciclaje, materiales compuestos, embarcaciones de alta velocidad

[a] Germanischer Lloyd, Hamburg/Germany,

e-mail: Henning Gramann (henning.gramann@gl-group.com); Reinhard Krapp (reinhard.krapp@gl-group.com);
Volker Bertram (volker.bertram@gl-group.com)

# Introduction

## Relevant IMO activities

The future IMO Convention on Ship Recycling focuses on safe and environmentally sound ship recycling, without compromising the operational safety and efficiency of ships. The whole life-cycle of ships is addressed, including dismantling and recycling or disposal of ships taking into account all materials contained. The convention requires for all ships above 500 GT a compendium of detailed information related to installed materials, which must be kept up-to-date during the entire operating life of a ship. In addition to this, the proper handling (including occupational health and safety, as well as environmental protection measures during dismantling of the materials at the ship recycling facilities) is a key issue of the convention and therefore will have to undergo a comprehensive certification process as well.

The core of the above mentioned convention affecting building and operation of ships will be the Part 1 of the "inventory of hazardous materials" (IHM), which is analogous to a Hazardous Materials blueprint. With this IHM, the location of hazardous materials contained in equipment and structure of the ship shall be easily determined. The basis for the IHM is the so called "Single List", which is a summary of materials which are considered to be potentially hazardous. The Single List consists of four tables, of which Table A and Table B are relevant for the IHM in the building and operational phase of the ship, see Table I.

For preparation of the IHM, all necessary information should be requested during the design and construction phase of a ship by the building yard, and during new installation of components on board existing ships by the owner or yard, depending on contractual arrangements. Manufacturers and suppliers must check all used components, equipment and coating systems against these two tables and provide this information to the shipyard. The shipyard collects this information and summarizes it in the ship specific IHM, which after delivery has to be kept up-to-date permanently. This will become part of shipboard tasks throughout the operating life of the ship. The updated IHM will be reviewed during inspections and prior to delivery to a recycling facility. Existing ships will also have to comply, but the IHM will be prepared by experts and cover materials of Table A only.

The transition to this future ship recycling and disposal management involves several challenges. *Gramann et al.* (2007) focus on 'administrative' aspects, namely the necessary IT (information technology) support for creating and maintaining data bases with inventories of materials on board ships. We will focus here on the special challenges that high-speed craft (HSC) pose due to the different nature of the material mix usually found in these vessels.

## Relevant ISO activities

ISO is developing its 30.000 series for "ship recycling management systems", which will set up international requirements for certain aspects related to ship recycling. In particular these standards will define "safe and environmentally sound ship recycling facilities", best practice for ship recycling facilities, guidelines for selection of ship recyclers including a pro form contract; set out the requirements for bodies providing audit and certification, and the standard on information control for hazardous materials in the manufacturing chain of shipbuilding and ship operations. It has not been decided whether the ISO 30.000 will also include guidelines on surveying of ships for hazardous materials, minimum amount or content of hazardous materials to be reported, or on methods for removal of asbestos.

An industry standard like the ISO 30.000 series shall positively affect the strategies for the interim period until the IMO convention enters into force, providing a common voluntary standard outside of legally binding regime. ISO 30.000 may contribute also to successful implementation and compliance with the future IMO convention. It may provide unified standards and more guidance to all stakeholders involved than any legal instrument can provide. The main focus is on shipbuilding and the recycling preparations and processes. The standard

Table 1. Tables A and B of the Single List of IMO

| No. | Materials | | Legislation | Threshold Level | Proposed Threshold Level |
|---|---|---|---|---|---|
| A-1 | Asbestos | | SOLAS | Not Provided | 0 ppm |
| A-2 | Polychlorinated Biphenyls (PCBs) | | Stockholm Convention | 50 ppm | 50 ppm |
| A-3 | Ozone Depleting Substances | CFCs | MARPOL, Montreal Protocol | Not Provided | 0 ppm |
| | | Halons | | | |
| | | Other fully halogenated CFCs- | | | |
| | | Carbon Tetrachloride | | | |
| | | 1.1.1- Trichloroethane (Methylchloroform) | | | |
| | | Hydrochlorofluorocarbons | | | |
| | | Hydrobromofluorocarbons | | | |
| | | Methylbromide | | | |
| | | Bromochloromethane | | | |
| A-4 | Organotin compouds | Tributyl Tins | AFS Convention | 2500 ppm | 2500 ppm |
| | | Triphenyl Tins | | | |
| | | Tributyl Tin Oxide (TBTO) | | | |

| No. | Materials | Legislation | Threshold Level | Proposed Threshold Level |
|---|---|---|---|---|
| B-1 | Cadmium and Cadmium Compounds | RoHS (2002/95/EC), ELV (2000/53/EC) | 100 ppm | 100 ppm |
| B-2 | Hexavalent Chromium Compounds | | 1000 ppm | 1000 ppm |
| B-3 | Lead and Lead Compounds | | 1000 ppm | 1000 ppm |
| B-4 | Mercury and Mercury Compounds | | 1000 ppm | 1000 ppm |
| B-5 | Polybrominated Biphenyl (PBBs) | RoHS (2002/95/EC) | 1000 mg/kg | 1000 mg/kg |
| B-6 | Polybrominated Dephenyl Ethers (PBDEs) | | 1000 mg/kg | 1000 mg/kg |
| B-7 | Polychloronaphthalanes (more than 3 chlorine atoms) | Japanese Law | Not provided | 0 ppm |
| B-8 | Radioactive Substances | 96/29 EURA TOM | Becquerel | No threshold |
| B-9 | Certain Shortchain Chlorinated Paraffins (Alkanes, C10-C13, chloro) | AFS Convention | 1,00% | 1% |

can be applied to all ships and all facilities, without any size limits and independently from the recycling countries ratification. Therefore more facilities can fall under a unified standard than what is possible under the future IMO convention. However, the basis for the ongoing development is that nothing will contradict the IMO requirements.

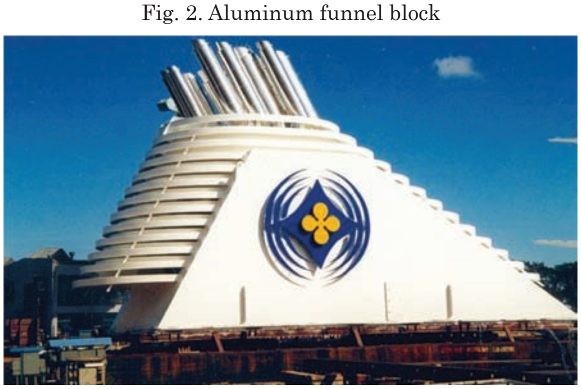
## HSC materials

Lightweight construction is essential for HSC, having a decisive influence on displacement, draft and thus power consumption for given speed. Lightweight construction is also frequently chosen for superstructures of other ships (like passenger ships or naval vessels) due to stability constraints. Frequently, aluminum and composite materials (like fiber-reinforced plastics (FRP)) are chosen as materials to reduce weight in critical structures, *Fach and Rothe (2000), Fach (2002)*.

Aluminum alloys of the 5000 series (AlMg alloys) and the 6000 series (AlMgSi alloys) are commonly used for fast lightweight ships, Fig.1 and Fig.2. The 5000 series alloys are more corrosion resistant in the marine environment and therefore primarily employed for plates of the shell, decks and built-up girders. The 6000 series alloys are easier to extrude and therefore frequently used for extruded sections, but being less resistant to corrosion they are generally restricted to internal structures, *Bryce (2005)*. Both series alloys feature good weldability.

Fig.1. Aluminum catamaran

Fig. 2. Aluminum funnel block



FRP and other composites are used in assorted applications, Figs.3 to 6:

- For hulls in short vessels (pleasure craft, small navy craft, life boats, etc.)
- In naval vessels, for integrated masts, hangars, etc. for stealth and weight reasons, *Beauchamps and Bertram (2006)*.
- In propulsion: propeller shafts, propellers, rudders, etc.
- In equipment and outfitting: boat davits, furniture, deck gratings, deckhouses, insulation

Composites have been proposed also for ship repair. Plastics are found in a variety of small structures on board ships (cables, fixings, etc.).

There is a variety of different FRP materials, due to assorted combinations of reinforcement material (fibers), laminating resins and core material:

- For reinforcement, generally glass, carbon and aramide fibers are used. More recently, natural fibers have been advocated, also within the context of recycling properties, *Umair (2006)*. Carbon and aramide fibers have high tensile strength. The fibers are available in the form of rovings, mats, fabrics and non-woven fabrics and combinations of these. These materials allow tailor-made non-isotropic strength properties (depending on fiber orientation), but also quasi-isotropic behavior achieved by the respective laminate construction.
- The main laminating resins used are polyester, vinyl-ester and epoxy resins. Vinyl-ester and epoxy resins are highly resistant to hydrolysis, i.e. they absorb insignificant amounts of water and the risk of osmosis is practically excluded.

Sandwich structures are more or less complex mixtures of materials. These structures consist of a face material and a core, bonded together by a putty or adhesive bond (typically polyester). The faces mainly support the tensile and compressive stresses of the sandwich in bending, and the core material mainly supports the shear stresses. Face materials may be metal or composites like carbon fiber composites. Core materials available for sandwich

Fig. 3. FRP in superstructure of 33 m HSC yacht

Fig.4. Composite louver

Source: www.ebertcomposites.com

Fig.5. Carbon-fiber laminate propeller shafts

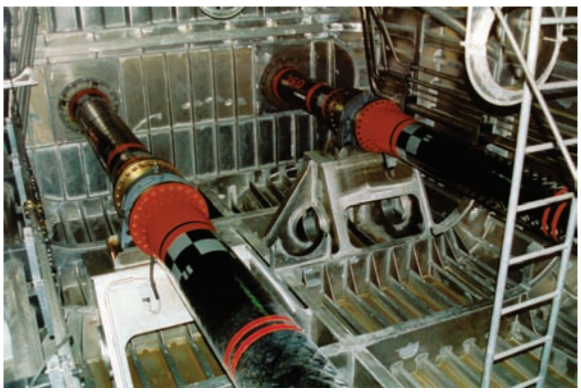
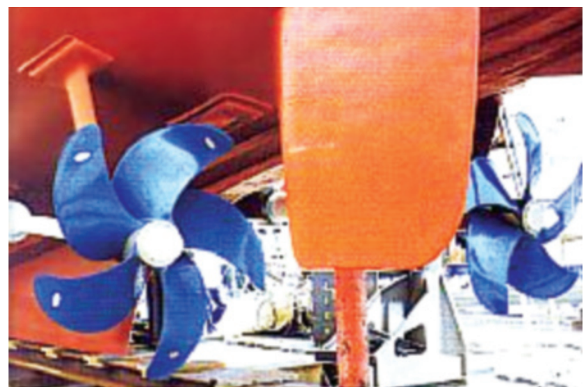


Fig.6: Contur® propeller of AIR Fertigung-Technologie GmbH



laminates are generally PVC foams, polyurethane (PUR) foams, polymethacryl (PMI) foams, balsa wood and honeycombs (thin aluminum or stainless steel plate honeycombs) as well as aramide paper (Nomex honeycomb). PUR foams are rarely used, *Müller (1990)*. See also *Umair (2006)* for a more detailed review of composites used in engineering particularly in shipbuilding. *Hedlund-Aström et al. (2005)* give composite mass data for the Swedish Visby class corvette. The ship contains 50 t carbon fibers, 40 t vinylester as matrix filler, 40 t of core material in sandwich structures (mixture of PVC and polymer of poly-urea/polyamid), 20 t of putty material (mainly polyester).

Sandwich structures in ships may contain assorted metallic inserts and embedded equipment. They may also contain hazardous materials. For example, the Visby class corvette sandwich structures contain 9 t of chlorine and 0.4 t of lead in the core material, in addition copper oxide in the bottom color and copper in the embedded electrical devices, *Hedlund-Aström et al. (2005)*. When chlorine is heated (e.g. during cutting operations), hydrochloric acid and dioxin is formed. Lead and copper affect health when consumed in food or drinks.

Recycling facilities specialize mainly in metal recovery. However, ships contain a multitude of materials, including composites. Composite materials are relatively young compared to the traditional metallic structural materials. Consequently, there is little experience in the industry on disposal and recycling techniques for these materials. However, increasing environmental demands from customers (navies) and authorities will force the industry to face this issue. While hazardous materials are at present the first priority problem to be solved, composite recycling and disposal will definitely be an issue for IMO regulations in the future.

In addition, recycling of FRP boats is an issue. These boats are not subject to IMO regulations and usually also outside direct class supervision. *Hayashi (1993)* estimates 30000 FRP boats built each year in Japan alone. Since disposal of these boats at the end of their life-cycle is expensive (estimated to exceed 940 Euro per boat just for the mechanical crushing, and more than 1250 Euro per boat when transport costs are included), illegal disposal of FRP boats along rivers, canals and in ports is a problem.

Traditionally, the most economical end-of-life options for composites were landfill disposal and waste incineration. However, since 2004, landfill disposal of composites has been forbidden in most European Union (EU) member states. Incineration of plastics is problematic due to the toxic byproducts. The EU End-of-Life Vehicle directive, adopted in 2003, requires 95% of each vehicle manufactured after January 2015 must be reused or recovered. These political constraints drive the dynamic evolution of a composite recycling industry. Naval architects can benefit from practice in other industries that have extensive experience with composites, namely the automotive and the aerospace industries. "Recycling and disposal of composites create issues that must be addressed. One such issue concerns end-of-life aircraft structures that contain carbon fiber composites coated with hexavalent chromium primer. These composites that are coated with hexavalent chromium can be classified as hazardous waste and thus may not be disposed on land due to possible leaching of the chrome into the ground.", *N.N. (2003)*. Indeed, the cost to dispose of a hazardous waste can be more than 20 times the disposal cost of a non-hazardous solid waste in EU. Thus, materials should be disassembled and sorted to reduce those parts containing hazardous substances to a minimum.

## Recycling and disposal

### General considerations

The following waste hierarchy is suggested for waste management:

- **Reuse or product recycling:** The product is kept in its shape, dismantled and reused, sometimes after an upgrade involving energy input and additional new material. For composite structures, this could mean cutting large (flat) panels from the hull structure to be reused in other structures. Problematic paint coatings need to be removed by sand blasting or affected parts of the structure are not reused. Reuse means material continuing to circulate. It is then important to have control on hazardous materials contained. Only part of the structure can be reused. The remaining part must then be treated according to one of the following methods.
- **Material recycling:** Composite recycling efforts in the past mainly concerned grinding, shearing, chipping, or flaking the composite into suitable size to be used as filler material in new molded composite parts, e.g. as filler mixing with cement or forming plates similar to plywood.
- **Chemical recycling:** The waste is decomposed into its original raw materials or directly transformed into other petrochemical raw materials. The waste is generally first mechanically crushed to increase the material surface. This results in a higher efficiency of the chemical process. Technically viable processes for composites are pyrolysis, hydrolysis and gasification. Pyrolysis is most frequently discussed. In pyrolysis, the polymeric component is thermally decomposed into smaller hydrocarbon molecules, which can be used as fuel. Remaining material (fibers, metallic parts) are then further recycled. Pyrolysis keeps thus fibers largely unbroken. However, this pyrolysis is expensive and only practicable to a certain plate size. Hydrolysis is used e.g. for PVC cores in sandwich panels. At present, none of the chemical recycling options are economically viable for commonly used glass fiber composites in the marine industry.
- **Energy recovery:** The waste is incinerated in appropriate installation recovering energy. The option depends on the caloric value of the waste. A threshold value higher than 11 MJ/kg is required in Europe to allow incineration for energy recovery. Carbon and aramide

fiber composites are well above this level, many glass fiber composites are below this level. Mixing with other material to increase the caloric value is not allowed. For carbon fiber composites, proper precautions must be taken to avoid the release of small fibers into the environment that may cause electrical interference problems, *N.N. (2003)*.
- **Disposal:** Waste may be disposed in waste incineration plants or landfills. Disposal of high-caloric waste in landfills is forbidden in the European community since 2005.

The capability to sort dissimilar materials, composites from metals, is the first step in recycling composites. Composites should be sorted by different reinforcement and filler/matrix materials. The composition of the composites determines the further processing. More valuable carbon reinforced composites, for example, will be recycled extracting the carbon fibers, while glass fiber reinforced composites may still end up in landfills (in some countries).

## Aluminum

Aluminum is often called a material of perfect recyclability since the secondary metal is recovered using only 3% of the energy consumed in the production of virgin metal by electrochemical purification, www.world-aluminium.org. Practical aluminum alloys, however, include various additives such as silicon, iron, copper, manganese, magnesium, zinc, etc. Accordingly, while recycling of scrap has progressed considerably with cast products which allow a large amount of additives, rolled and shaped products which permit only a small amount of additives have been manufactured preferably from raw materials rather than recycling products. Research is active to extend also the recycling of aluminum alloys into rolled and shaped products. For the shipbuilding industry, the approach is straight-forward. The aluminum alloys in the ship structure are on record, disassembly follows standard procedures, and after sorting the different alloys, the aluminum alloy parts can be recycled in dedicated recycling facilities. The value of the scrap depends on a number of factors. Coated plates require additional processing prior to recycling and this reduces the amount paid for this scrap.

## Glass-fiber composites

Glass fiber composites are the most popular composites in the boat industry. While glass can be easily recycled, the recyclate is not commercially viable due to the already low price for virgin material.

Some glass fiber composites (with lower glass fiber content) have enough caloric value to be used in energetic recycling. The main benefit is heat which may be used for district heat, steam generation, electricity generation or directly in chemical, steel or cement plants. Additional byproducts are gypsum and slag with a high content of molten glass. These are widely used in construction materials, e.g. concrete and aerated concrete. Slag without glass content may need further processing to remove hazardous substances, slag with glass content usually is unproblematic as the hazardous substances are bound in the glass. In addition to gypsum and slag, considerable amounts of ash are created. The disposal of this ash (typically in landfills) is expensive. In summary, energetic recycling of glass fiber composites is problematic due to their low caloric value and the large amount of residual ash.

At present, there are no economically viable options for chemical recycling of glass fiber composites, although it is technically feasible, as shown e.g. by *Hayashi and Yamane (1998)* for FRP boats.

In mechanical recycling, the recyclate is mainly used as filler material. Recycling glass fiber composites in Sheet Moulding Compounds (SMC) and Bulk Moulding Compounds (BMC) has been successful. These techniques allow relatively high degrees of recycled composite materials as filler, but involve high pressures and high temperature. Applications include electrical equipment, car components (headlights), and housings for electrical appliances. Recyclates have been used also for outdoor construction materials, e.g. for road cover, road markers and insulation panels. However, the amount of waste from glass fiber composites exceeds so far largely the demand in recycling products with the applications found so far.

Fig.7a. Building material from recycled composites. Glass foam plates

Fig.7b. Building material from recycled composites. Gypsum blocks

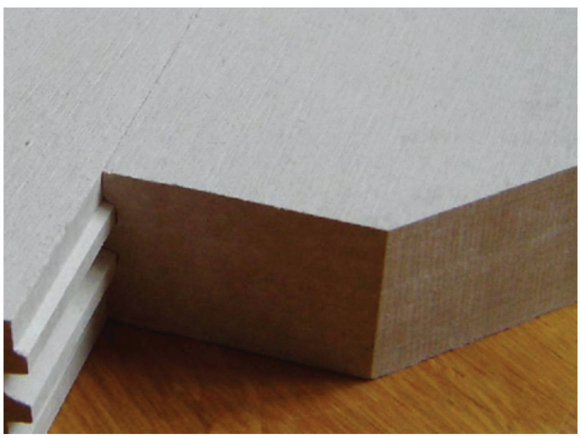


Fig.7c. Building material from recycled composites. Headlight

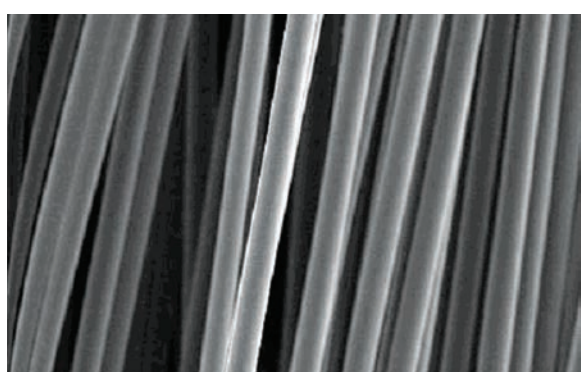
Glass fiber composites with high polyester content (60% unsaturated polyester) can be used in the cement industry. Process complications appear with the glass fibers blocking filters and dust generation requiring good filters for work place protection. Otherwise this application appears attractive as it leaves almost no residues, but it requires a large constant supply for the production plant. An estimated 10000 to 20000 t/a will be needed as supply.

## Carbon-fiber composites

Carbon-fiber composites offer more attractive options for recycling. Acid digestion could be used to reclaim the carbon fibers, but appears to be impractical from an environmental point of view. Acid digestion uses hazardous chemicals and creates a mixture that will require further processing. Adherent Technologies Inc. (ATI), www.adherenttech.com, have been successful in separating carbon fibers from carbon fiber-reinforced epoxy composites and reclaiming valuable carbon fibers, Fig.8 and Fig.9, *N.N. (2003).*

Fig.8. Reclaimed carbon fibers, *N.N. (2003)*

Fig.9. Microscopic view of reclaimed carbon fibers, 99.8% pure, *N.N. (2003)*



ATI employs catalytic conversion to recycle composites. Catalytic conversion produces chemicals or fuels from scrap or waste products. By-products generated include phenolic compounds used in certain adhesives. The reclaimed carbon fibers have very similar properties to virgin fibers, but are shorter. Reclaimed carbon fibers cannot be reused in applications requiring longer, continuous carbon fibers. However, the demand for chopped and milled carbon fiber is growing. Applications for such recycled carbon fibers are for example housings of cellular phones and laptop computers. "Methods exist today by which carbon fibers and prepregs can be recycled, and the resulting recyclate retains up to 90 percent of the fibers' mechanical properties. In some cases, the method enhances the electrical properties of the recyclate because the carbon recyclate can deliver performance near to or superior to virgin material. All that remains is to create demand for recycled fiber by packaging it in a form useful to end-users," *Davidson (2006)*. In summary, once the carbon fiber composite has been singled out and sorted, recycling is possible by dedicated facilities.

## Sandwich panels

Before cutting composite or sandwich structures, embedded electrical equipment and metallic inserts as well as the content and nature of hazardous material need to be known. The position of metallic parts is indicated in technical drawings. Hazardous content and position will have to be documented, according to the current draft convention from IMO.

The processes of dismantling and further mechanical preparation for recycling (like crushing and milling) involve potential health risks due to exposure to dust, smoke, gas, sharp fibers and other sharp material parts, and noise. For example, hydrochloric acid and isocyanates are generated when heating the PVC core in sandwich structures. These risks can be contained through proper workplace and personal protection, as regulated by national occupational health and safety regulations, but implementation throughout the ship recycling processes might remain difficult due to different circumstances (climate conditions, accessibility and additional need of space when wearing or carrying personal protection equipment, etc.).

*Hedlund-Aström et al. (2005)* discuss the various options for recycling and disposal of sandwich structures in ships:

- Reuse: Cutting large panels from the hull structure allows reusing sandwich material. Hazardous material bound in the core may be safe to cut and transport, but authorities like environmental agencies should be consulted. Metallic equipment or inserts not removed during disassembly are either dismantled or cut away during cutting to final size.
- Mechanical material recycling: Milling the complete sandwich has been applied to a sandwich structure consisting of a face of glass-fiber reinforced polyester and Divinycell core, *Hedlund-Aström and Olsson (1997)*. The recycled sandwich mixture was blended with polyurethane. Plates similar to plywood or chipboard were manufactured through expansion in a form.
- Recycling by pyrolysis and hydrolysis were discussed. While technically feasible, they do not appear to be economically viable options.

## Disassembly

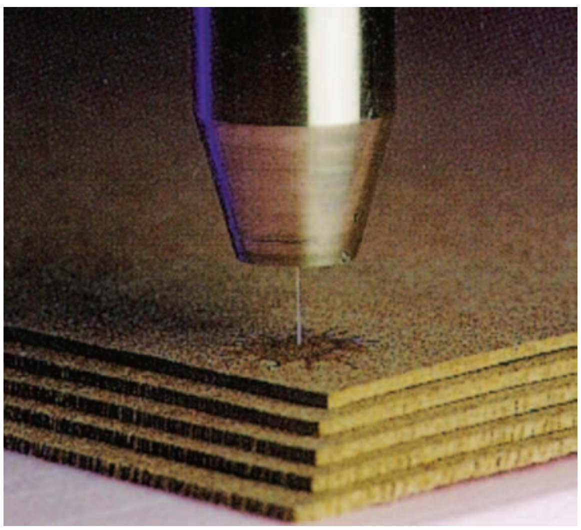
There are various ways to cut composites during disassembly:

- Mechanical cutting with power saws or other cutting tools, Fig.10. The generated dust may in most cases require appropriate protection for the workers. The tools are cheap and can be portable.
- Water-jet cutting which is another form of purely mechanical cutting using a jet of water at high velocity and pressure, or a mixture of water and an abrasive substance, Fig.11. The process is essentially the same as water erosion found in nature but accelerated and concentrated by orders of magnitude, able to cut thin metals and composites. The technology is used in aerospace and other industries. The advantage is that there is no heat and no chemical process involved. Portable water-jet cutters are available on the market.

Fig.10. Mechanical cutting of boat hull


Source: www.slashbuster.com

Fig.11. Water-jet cutting



Source: wikipedia

- Thermal cutting using oxy-acetylene; this method is frequently used for cutting steel structures in ships. The approach is problematic for most composites due to potential toxic by-products in burning plastics.
- Plasma cutting; the cutting is usually performed under water reducing dust and fumes problems, but installation are not always portable and relatively expensive, though cheaper then laser cutting. The cutting speed is relatively low compared to thermal cutting, which is an important factor for cost effective ship dismantling.
- Laser cutting; the heat is highly focused reducing health hazards, but installations are expensive and not portable.

## Problems to address

### Identification of material

To maximize the recovery of material and generate the best financial return, the materials must be efficiently sorted before post-processing. A significant concern in recycling and disposal is the proper identification of various materials in ships to be scrapped, and how to sort and recycle this mix.

Recycling companies must know what they shall recycle. It could be a basic epoxy matrix composite, or it could be a brominated resin matrix, with all the associated toxic complications. At present, no sophisticated and reliable knowledge/experience exists. In newbuildings, this could be documented from the start in a material database. In the large fleet of existing ships of different age, we will be commonly faced with information gaps concerning the material composition.

Just before disassembly, material samples can be taken and analyzed. However, this type of destructive testing is usually not an option while the ship is still in service. Non-destructive testing of composites is subject to research, e.g. at the Fraunhofer research centers in Germany, and is expected to drift into industry practice in due time.

An example may illustrate the scope of work needed in compiling the variety of multi-layered composites found in modern ships. The example shows extracts of the files for the cruise vessel AIDA Diva: The deck structures use sandwich panels similar in structure to those of the walls. These panels consist of stone wool as core material and zinc plates as covers, lacquered or covered by foils. The files do not give the thickness of the cover plates; the density of the core material is 130 to 150 kg/m$^3$. Decks, hull and bulkheads are equipped with insulation against noise, fire and heat. This insulation consists mainly of mineral wool (stone, glass). The floor of the Captain's Cabin 1001 is equipped with a fire-resistant insulating floor of type A 60. This floor insulation is labeled Tefrolith M. Furthermore, there is a layer below the carpet labeled IMO Lay.

## Product alternatives

The automotive industry has investigated composites based on natural organic materials (cellulose, sisal, jute, hemp, etc.) as alternatives to classical glass or carbon fiber composites, *Marek et al. (2000)*. These reinforcements are reusable, good insulator of heat and sound, degradable and cheap. They are less fire resistant and their quality varies naturally more, moisture may cause fibers to swell and price may fluctuate according to yield of crop. Despite these shortcomings, natural fiber composites are expected to see wide use in the automotive industry, due to their light weight compared to glass fibers and their recycling properties. Little is known about natural fiber composites in the shipbuilding industry. The moisture problem and uncertainties about the long-term behavior of natural fiber composites make them unlikely candidates for the marine industry.

## Markets and logistics

Energy recovery is at present not a viable option for the popular glass-fiber composites. However, it is technically feasible. *Hayashi and Yamane (1998)* present for example a movable disposal system for FRP boats. The movable system, installed on two trailers, reduces transportation costs and allows decentralized service. The system is set up to incinerate most boats at original size, avoiding the pre-processing cost of crushing. The resulting stone-like solid with high silicone content are compact and can be used as stone pavement, cement, or core material for various insulation material. However, although a prototype was presented 10 years ago, the idea failed due to economic aspects. Considerable process improvement to reduce cost or subsidies would be required to change this.

The industry needs a network of specialized recycling facilities for composite structures. The decommission shipyard will typically focus on breaking the ship apart, sorting and channeling the individual items and materials for further processing by dedicated subcontractors or buyers. The task of the shipyard in this respect is identifying the composite, disassembling to the appropriate level using the appropriate technology, sorting and seeing that it gets to the appropriate dedicated specialist. While networks for more traditional materials like metals are established in shipbuilding, networks for composites still need to evolve. The relatively small amount of composite material processed in shipbuilding industry necessitates using networks and facilities developed by related industries (aeronautical, automotive, mechanical engineering).

## Dissemination

Training and dissemination of knowledge concerning the problems and procedures will be a key issue for the transition of the industry towards a life-cycle management approach, particularly for the less familiar and more problematic materials in shipbuilding, like composites. Disposal and recycling add aspects for consideration already in the design stage. Besides aspects like 'Design for production', 'Design for operation' and 'Design for maintenance', we should then train engineers to consider aspects of 'Design for recycling', *Lamb (2003). Marek et al. (2000)* recommend considering two fundamental aspects for 'Design for recycling',

- Structural design (Is the item easy to disassemble?)
- Material selection (Can materials difficult to recycle be replaced by alternatives easy to recycle?)

*VDI (2002)* discusses Design for Recycling in more detail, drawing on experience for diverse mass production industries in Germany. Generally applicable guidelines for Design for Recycling are:

- Avoid problematic materials
  Regulated or restricted materials may require expensive disposal at the end of the life-cycle. Materials incompatible for recycling will have to be separated at considerable expense. Painting of parts generally contaminates parts. For composites, it is often preferable to use colored plastic resin.
- Use 'Design for recycling' materials
  Wherever possible, use recycled material and use recyclable material. In composite structures, use compatible adhesive bonding to allow recycling. Suitable combinations

may be found in discussion with experts for adhesives. Use materials which can be recycled as a mixture.

- Reduce complexity
  Reduce the number of material types used.
- Make disassembly and sorting easy
  Use route wiring. Use modular design. Make components of different recyclable material easy to separate. Mark plastic parts according to standards, *ISO (2000)*, and in a way that allows the marking to be read even after 30 years in a maritime environment.

Many of the general guidelines coincide with advice given for Design for Production.

*Landamore et al. (2007)* show how assessing the disposal costs in the design stage may influence material selection, applying life cycle cost analysis to inland leisure craft.

## Conclusion

Unless markets for recycled composites materials evolve, the options for certain composite materials at the end of the life-cycle are limited:

- Export of this 'problematic' waste to countries with more lenient legislation. However, there are efforts to restrict this export both on national level of developing countries and on international level. It may not be a long-term option.
- Incineration or landfill with special permit and subject to a fee or tax.

As a consequence, these composites may then reduce the value of a decommissioned ship.

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