RESEARCH AND DEVELOPMENT RESULTS FOR DISMANTLING AND DECONTAMINATION APPLICATION

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ABSTRACT

The paper gives an overview about research and development results for dismantling and decontamination techniques, including new investigations and applications for plasma arc cutting, contact arc metal grinding/cutting techniques and dry ice laser beam blasting. Different physical effects can be distinguished for removal/dismantling and decontamination technologies. These effects may be classified by their chemical/electrochemical, mechanical or thermal effects. **Plasma arc cutting** is already established for dismantling tasks, especially for activated components to be cut under water. Based on equipment developments at the Institute of Materials Science in Hanover, Germany, the maximum cutting thickness through stainless steel under water could be increased up to 130 mm. For the application of cutting the thermal shield of the Multipurpose Research Reactor (MZFR) in Karlsruhe, Germany, a water depth of 4 m is necessary for effective radiation protection. Successful 1:1 scale tests using a 5-axis robot system have already been performed. **Contact arc metal cutting and grinding**, which are mainly used underwater, could be handled under nearly no restoring forces, unlike mechanical cutting techniques. This results in an application flexibility that takes into account the possibility of cutting complex geometries and structures up to more than 100 mm effective cutting depth. For contact arc metal cutting, high current arcs are used to melt the material, transferred by a carbon reinforced graphite sword. The molten material is blown out of the cutting kerf by a water stream running along the sword. The maximum cutting depths is only limited to the effectiveness of the water stream. **The dry ice laser beam blasting process** is a new development from the Institute of Materials Science using a dry ice jet in combination with a high power diode laser system in a hybrid process. The physical effects applied are thermal shock effects based on the heat input through the laser beam additional to the cooling of the dry ice as well as mechanical effects based on the impact of the dry ice particles accelerated onto the work piece. Dry ice laser beam blasting can be used for the cleaning of surfaces and the de-lamination of surface coatings as well as for the removal of layers of solid material like concrete or ceramic tiles.

INTRODUCTION

Decontamination and dismantling techniques use various processes in decommissioning facilities (e.g., plasma arc cutting, contact arc metal cutting and grinding, and a dry ice – laserbeam blasting process), especially those that are contaminated by radioactivity. Decontamination methods may be classified as either surface cleaning or surface removal. In this paper only surface removal is considered. On most contaminated parts the major fraction of contaminants is deposited in a surface layer, for example an oxide layer. The remainder is distributed by grain boundary diffusion within the base material up to a penetration depth of some 90 µm, for example the piping in a primary system. Often a few millimeters underneath the component surface activation is low enough that conventional disposal is possible. Therefore, it is common to reduce the waste by removal of surface layers and coatings. The coating materials may be of metallic, ceramic, metal-ceramic, or organic nature. A presentation of state-of-the-art decontamination techniques is given in [1], [2].

Analogous to decontamination techniques a large variety of dismantling techniques are state-of-the-art and are currently being used. In addition to the above-mentioned selection criteria, process safety, cutting speed, remote operated handling, and reduction of emissions will be compared. The objective of this paper is not to provide an overview of all decontamination and removal/excavation techniques, but to illustrate the thermal processes used in decontamination and excavation, the potentials of new developments, and to discuss the research and development of state-of-the-art decontamination and dismantling techniques performed at the Institute of Materials Science. Further information concerning the described technologies is available in [3-5] and from European Commission reports.

Decontamination Techniques

A major reduction of waste for final storage can be achieved by decontamination. When selecting a suitable decontamination technique, one focus is on the material to be decontaminated. There are metallic, organic (e.g., paint, plastic coatings, and parts), mineral (especially concrete), and ceramic (e.g., tiles) work pieces and surfaces. Decontamination techniques may be divided into the cleaning of surfaces and the de-lamination of surface coatings. In general, decontamination techniques are based on chemical, electrochemical, mechanical, and thermal mechanisms or use a combination of these [6].

- **Chemical and electrochemical:**
  Chemical removal techniques are based on a reaction or dissolution of a substance with the material.

- **Mechanical:**
  Mechanical processes include cutting technologies and impact technologies. Cutting technologies cut out the material with an edge. Impact processes are based on particle or jet impact to crack the material and remove it.

- **Thermal:**
  Thermal processes may be divided into methods that apply heat and methods that remove heat from the material (cryogenic methods). Both make use of changes of materials properties, e.g., brittleness at low temperatures or, in multilayer systems, different coefficients of thermal expansion. Heat may be applied to facilitate a chemical reaction or to degrade the material.

Frequently, these methods are combined to remove material. Abrasion and impact mechanisms, for instance, typically occur simultaneously. The major removal techniques and their physical effects are presented in **Table I**.

Table I. Classification by Physical Effect for Removal Techniques

chemical / electrochemical	chemical		dilution molten salt oxidation / reduction ...
	electrochemical		
mechanical	cutting	geometrically defined tool angles	lathe milling ...
		geometrically non-defined tool angles	grinding abrasives, dry abrasives, wet
	impact		waterjet dry ice impact blasting
thermal	cryogen		dry ice liquid nitrogen ...
	heat		laser ...

Thermal Processes

Dry Ice Blasting

Dry ice blasting has been in use for several years to clean surfaces and remove coatings without damaging the base material surface. The blasting medium consists of carbon dioxide snow compressed to pellets of 1 to 3.5 mm in diameter and 2 to 10 mm in length. These pellets are used in solid–gas equilibrium at a temperature of -78°C. They are accelerated by a gas stream and directed to the surface. The gas jet reaches velocities in the order of 300 m/s with pellet velocities between 190 and 300 m/s [7]. Unlike other blasting techniques, dry ice blasting is not abrasive due to the low hardness of the dry ice pellets of 2-3 Mohs [8], [9]. The resulting gaseous carbon dioxide is sucked off together with the coating particles. The filtered gas stream can be discharged into ambient air with no secondary waste produced.

Dry ice blasting is based on the following effects: Upon contact, the cold carbon dioxide takes heat energy from the material to be treated. According to measurements by Haberland, temperature of the surface of a sheet metal is cooled down to -60°C, where –10°C is reached at a depth of 0.5 mm [10]. As a result, thermal stresses are induced in the material. In coatings with a different thermal expansion coefficient other than that of the base material, additional stresses are produced between coating and substrate. On impact, part of the kinetic energy of the carbon dioxide pellets is transformed into sublimation energy. The volume is expanded by a factor of 700 due to the phase change from solid to gaseous form. This expansion generates a shock wave on the surface to be treated, where these very fast variations of pressure cause a desired impact on the material. The third main effect is the kinetic energy of the pellets. Due to the low pellet abrasiveness, the effect of kinetic energy is low compared to other blasting processes.

Dry ice blasting alone yields good results in the removal of organic coatings and cleaning. In the decommissioning of nuclear facilities, dry ice blasting has been used for the decontamination of surfaces [2], [11]. Some organic coatings of elevated mechanical resistance, such as powder coatings or decon coatings, cannot be removed by dry ice blasting. It is also impossible to remove solid materials of metallic, ceramic or mineral nature.

Dry ice laser beam process

The dry ice laser beam process is a new technology that combines dry ice blasting with heat from a laser beam. By heating the surface around the area of the dry ice pellet impact with a laser beam, the effect of thermal stress is maximized and several materials are weakened. Contrary to laser ablation techniques, the material is not heated up to decomposition, but to some 100 C only. Generation of a plasma in the laser zone or melting and evaporation of the material treated is avoided to keep the effort required for cleaning the sucked-off gas low.

In tests, a 2 kW diode laser and standard dry ice blasting equipment were applied. A diode laser was chosen because of its compact size and comparably low investment costs. Poor beam quality does not result in any restriction of this application [12].

Application

Material removal from concrete and ceramic tiles can be accomplished with the dry ice laser beam process. The strong heterogeneity of concrete that consists of cement and aggregate does not lead to the selective removal of one phase only. In both concrete and ceramics, removal depth varies by up to 50% on the average, as the material is removed in splinters of up to 0.5 mm in size. A more detailed presentation of an experimental set-up and results can be found in [12]. For concrete, removal rates of 1500 cm^3/h and for ceramics of 650 cm^3/h (respectively) are reached, while removal depth is up to 5 mm and 3 mm and the maximum removal width is up to 80 mm. In Autumn 2004 tests were carried out with the dry ice laser beam process at the Forschungszentrum Karlsruhe (figure 1).

Removed particles may be separated from the gas stream by mechanical separation (cyclones, filters). Measurements of particle size in the gas stream of cascade separators show that 98% of the solid particles are larger than 0.5 μm and 99.9% are larger than 0.06 μm. Studies of filter residues by scanning electron microscopy revealed that the mineral particles are only broken mechanically and no melting of the material could be observed.

Re-contamination from removed material, which can be observed for many mechanical techniques like milling, is strongly reduced with the dry ice laser beam process. The operative range of this hybrid process is not restricted to concrete and tiles. The dry ice laser beam process can remove organic coatings that cannot be removed by dry ice blasting alone. The organic coating may be weakened or thermally disintegrated by the laser beam. Experiments on a thermoplastic and a duroplastic powder coating showed that the coating could be removed by the dry ice laser beam process when removal could not be accomplished by dry ice blasting alone [12]. The thermoplastic coating (polyethylene) was not disintegrated by the laser beam but the duroplastic coating (epoxy/polyester) was disintegrated thermally.

Usually, the dry ice laser beam process does not damage solid metal components. This process is suited for the removal of a non-metal coating from a metal substrate without damaging the metal component. Apart from the organic coatings mentioned, ceramic coatings produced by thermal spraying may be removed from metal substrates.

Fig. 1. Test of the dry ice laser beam process at the Forschungszentrum Karlsruhe

Dismantling Techniques

Classification of Dismantling Techniques

In view of the wide range of dismantling tasks, many different cutting techniques have been developed so far. In some cases, techniques used in sheet-metal manufacture have been adapted to the special requirements of decommissioning nuclear installations. Special techniques have been developed exclusively for such tasks. An overview is given in Table II showing mechanical/hydraulic, thermal, and chemical/electrochemical techniques. Due to the requirements associated with the decommissioning of nuclear installations, such as remote-controlled application, high process safety and efficiency, reduction of emissions, and underwater applicability, only a few of them can be employed in a controlled area.

Table II. Dismantling Techniques

mechanical/hydraulic	thermal	chemical/electrochemical
- Sawing - Shearing - Milling - Breaking - Grinding - Nibbling - (Diamond) Wire sawing - Microwave spalling - Abrasive water jet cutting - …	- Oxy-fuel cutting - Lance cutting - Plasma arc cutting - Consumable electrode oxygen jet cutting - Consumable electrode water jet cutting - Oxy-arc cutting - Arc-saw cutting - Contact arc metal cutting - Contact arc metal drilling - Contact arc metal grinding - Laser beam cutting - Electrical discharge machining - …	- Explosive cutting - …

Several specific methods are useful for dismantling and decontamination. Among these are electrochemical cutting techniques, electrical discharge machining and microwave spalling [5], [13]--[15]. Explosive cutting that was used in Niederaichbach, Germany, for the de-lamination of activated concrete structures, has been applied to a few decommissioning tasks, e.g., dismantling of the biological shield at the Elk River reactor in the United States of America [3], [16]. Arc-saw cutting with a rotating disc was developed in the USA and used for dismantling different reactor pressure vessels in the USA and the JPDR in Japan [3]. Other arc processes are discontinuous oxy-arc cutting and consumable electrode oxygen and water-jet cutting [3], [13], [17], [18]. Consumable electrode water-jet cutting has already been used for dismantling a pressure vessel and a steam dryer housing [3].

Mechanical cutting techniques with geometrically defined tool angles, such as sawing and milling, are characterized by rough and easy collectable residues (e.g., chips), high reaction forces, and low cutting speeds. Mechanical cutting techniques with geometrically non-defined tool angles, such as grinding and diamond-wire sawing, are characterized by process products consisting of small-grained dust (100-800 µm) in atmosphere or slurry when used underwater [13].

One of the first examples of abrasive water injection jet (AWIJ) dismantling is the biological shield of the JPDR in Japan. The first example of the abrasive water suspension jet (AWSJ) technique was applied at the VAK nuclear power plant in Kahl, Germany, by using a maximum water pressure of 200 Mpa to cut plate thicknesses up to 132 mm. The advantages of abrasive water jet cutting are in the small amount of aerosol used, the wide range of plate thicknesses cut, the multifunctional uses as in kerfing and de-lamination tasks, the applicability in atmosphere as well as underwater, easy remote handling, and low reaction forces. One disadvantage is in the secondary waste generation. Only a very small amount of waste is spread into the air as aerosols, most of the waste consists of sediment particles [19]-[22].

Thermal Cutting Techniques

Oxy-Fuel Cutting/Lance Cutting

Oxy-fuel cutting is restricted to mechanized, semi-remote as well as hand-guided dismantling of mild steel or stainless steel-plated mild steel structures [3], [23]. Hand-guided and semi-mechanized dismantling has been employed on plate thicknesses of 250 mm [24], [25]. When adding powder, oxy-fuel cutting also allows the cutting of stainless steel and concrete. In cutting tests, maximum cutting thicknesses have reached 320 mm for steel and 1200 mm for concrete structures. A major disadvantage is the high amount of aerosols produced during this process [3]. The lance cutting process can only be used for drilling and perforation cutting, e.g., prior to oxy-fuel cutting of thick structures (e.g., pressure vessels). Typically for this operation the cutting speed is low, the process is discontinuous and not suitable for automation. An undesirable amount of aerosols is also produced [3]. For dismantling tasks, various combined processes were developed, such as combinations of consumable electrode water jet gouging/oxy-fuel cutting and plasma arc gouging/oxy-fuel cutting [3], [26]. Research and development activities currently focus on high-pressure oxy-fuel cutting and mechanized underwater oxy-fuel cutting, especially for cutting stainless steel-plated mild steel structures [23].

Plasma Arc Cutting

In decommissioning, plasma arc cutting is the most commonly used thermal cutting technique for activated components and particularly reactor internals. The main advantages are: 1) high cutting speeds over a wide range of plate thicknesses, especially for cutting stainless steel, 2) applicability in atmosphere as well as underwater, 3) easy remote handling, and 4) low reaction forces. The maximum achievable cutting thickness in atmosphere is 150 mm and underwater 100 mm [3]. Several plasma torches based on principles like water-injection plasma arc, dual-flow plasma arc, contact ignition, etc. have been designed. For a fast remote-controlled replacement of worn parts, modular systems have been developed [3], [13]. For the dismantling of highly activated core components, characteristic amounts and emissions are given in [3], [26]-[28].

Research and development, as carried out in Gundremmingen, Germany [29], are aimed at reducing the kerf width and designing a personally guided “steady-cut system” [30] as well as at increasing plate thicknesses cut underwater and investigating plasma arc cutting up to a water depth of 20 m. A special plasma arc cutting system was developed for the dismantling of the multi purpose reactor in Karlsruhe. Based on this technology, safe and reproducible cutting of most difficult geometries of the moderator tank and thermal shield has been demonstrated at a test rig at the research reactor in Kahl. This system was developed by the Institute of Materials Science of the University of Hanover in cooperation with the Kjellberg Company for high thicknesses in particular and is suited for cutting sheet metal thicknesses of up to 130 mm at 4 m water depth and a maximum cutting current of 900 Amps (figure 2) [31].

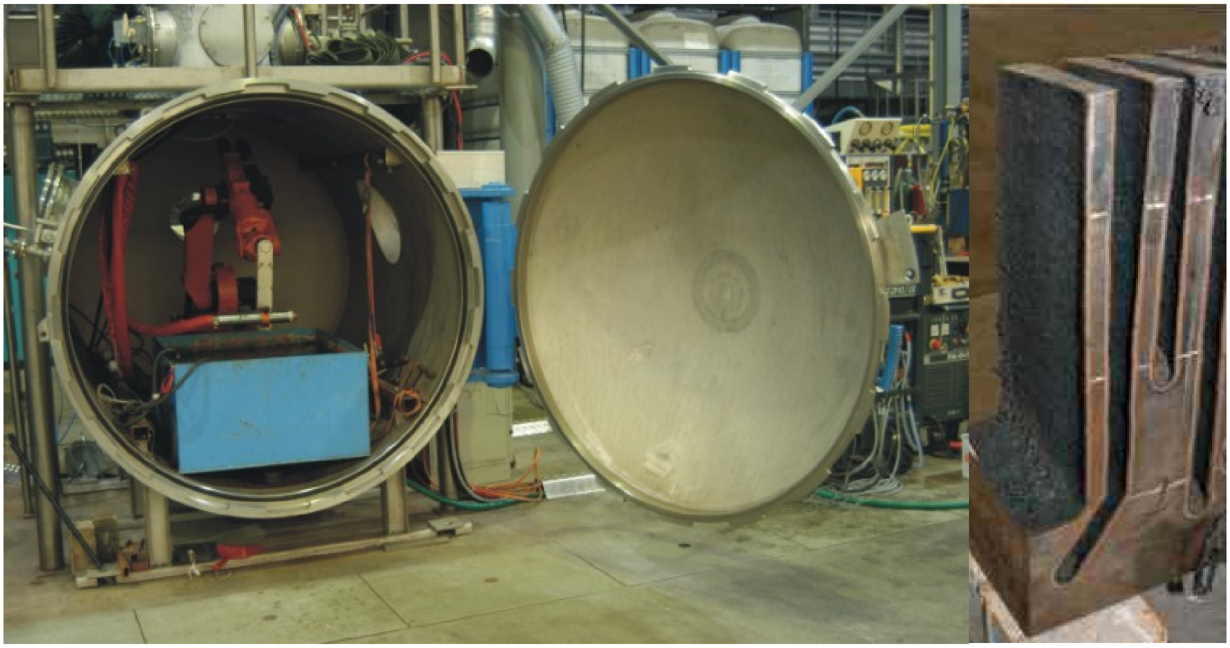


Fig. 2. Left: Test rig (pressure tank) at the Underwater Technology Center, Hanover. Right: Cutting edge of the mock up 70 – 130 mm; 5th section of the thermal shield, plasma gas: Ar/H_2, secondary gas: air, cutting current: 900 A, cutting voltage: 215 – 220 V, cutting speed: 240 mm/min (70 mm) – 90 mm/min (130 mm), cutting position: vertically descending – horizontal.

Laser Beam Cutting

Laser beam cutting, where applicable, is characterized by small cutting kerfs and precise cutting contours, small heat-affected zones, small tolerances, little distortion of the work piece, stress-free treatment, and high reproducibility. On the other hand, a high investment is necessary. The low efficiency of the lasers is coupled with a high-energy consumption. Laser technology can be used in many areas of dismantling nuclear power plants [32], [33]. When dismantling tanks or storage basins consisting of concrete walls lined with steel plates, for instance, cutting of the steel material is complicated. The metal sheets lie directly on the concrete and are difficult to cut mechanically. A special nozzle technique in combination with a hand-guided laser system was used in the nuclear power plant of Greifswald, Germany, to expel the molten material to the top surface of the sheet. Specific removal by suction of the released process emissions is also possible [34]. The mobility and flexibility of the fiber-optical hand-guided Nd:YAG laser are the main reasons why it is used in nuclear facilities. Among the prerequisites for this process is the availability of a hand-held laser processing head, characterization data, and a suction system for the aerosols produced [35] - [37]. Current research and development activities are dedicated to cutting asbestos materials as well as designing modular laser beam cutting systems for cutting in atmosphere and underwater.

Contact Arc Metal Cutting (CAMC), Drilling (CAMD), and Grinding (CAMG)

Contact arc metal cutting (CAMC), drilling (CAMD), and grinding (CAMG) are electro-thermal cutting techniques that cut conductive materials with Joule and arc heating (figure 2). **C**ontact **A**rc **M**etal **C**utting (CAMC) with a sword-like graphite electrode and a water curtain for blowing out the molten material is a thermal cutting technique that is currently used for decommissioning nuclear facilities [38]. Components of complicated design like tube-in-tube work pieces and components with re-entrant angles can be separated with a single cut using this technique. A state of the art of CAMC cuts 260 mm thick components. The kerfs show widths of 4 to 8 mm and wastage ranges from 20 to 25% [38]. A special CAMC tool with a turntable driving unit and an integrated process control for automatic cutting was developed for cutting tasks in Greifswald, Germany [39]. A related process, **C**ontact **A**rc **M**etal **D**rilling (CAMD), is a novel technology to drill holes or pocket holes without restoring forces. Using a warp mechanism, an automated fixing system was built [40], [41].

Another cutting technique is **C**ontact **A**rc **M**etal **G**rinding (CAMG) with a rotating electrode (figure 3). It opens up new fields of application, since materials for the cutting electrode, steel or carbon-fiber-reinforced graphite can be used and the cutting speed is very high. CAMG is capable of cutting work pieces of 15 mm thickness at a speed of 3 m/min. The wear of the rotating electrode can be reduced to 9% by appropriate parameter adjustments. The maximum cutting thickness is 40-50 mm [41], [42].

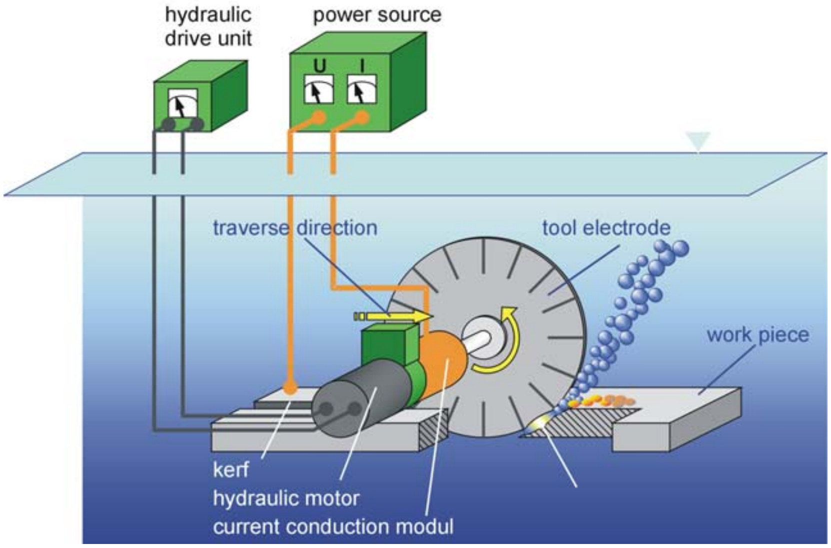


Fig. 3. Principle of Contact-Arc-Metal-Grinding (CAMG)

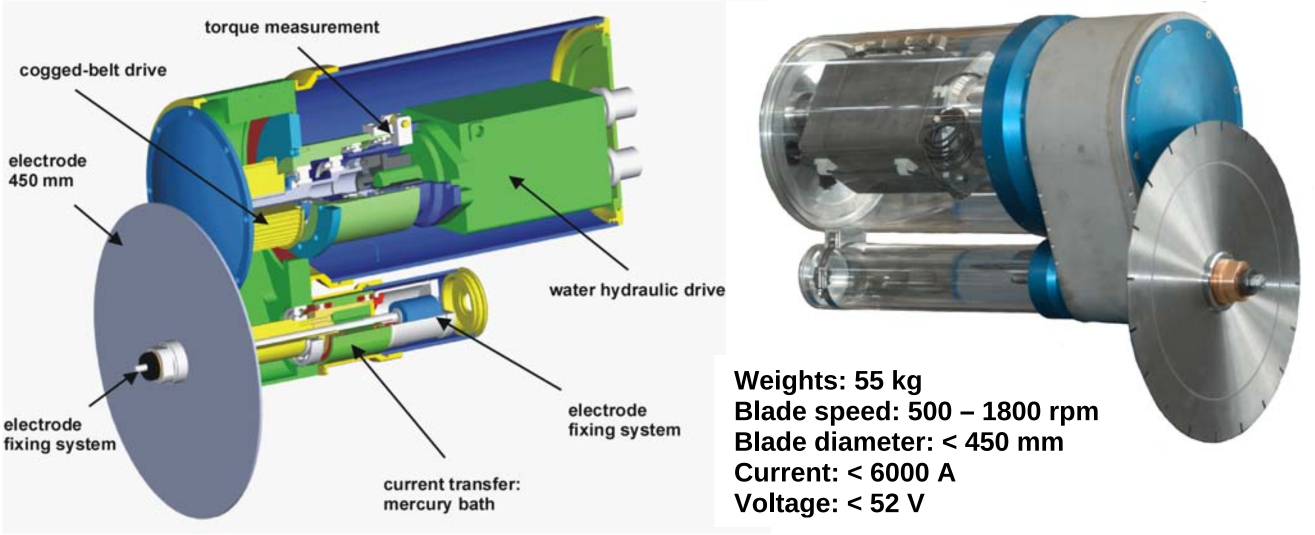
The CAMG uses a normal welding transformer for an energy supply. The basic concept of the tool is a water hydraulic motor for powering the electrode (max. 3.000 1/min). The work spindle has ceramic bearings and rotates in a multi-seal Hg-chamber (current conduction module) where the Hg conducts the work current to the rotating work spindle. With these techniques, very high cutting rates can be achieved, because the metal removal performance can be up to 40-150 kg/h (88-330 lb/h). Depending on the electrode thickness, the wide of the kerf is 3 – 6 mm and the quality of the cut edge is comparatively good and nearly right-angled.

To integrate CAMG in a modular cutting tool system, a CAMG-tool with following goals is under development:

- Cutting thick-walled and multiple components
- Electrode diameter from 200 mm – 450 mm
- Electrode (Blade) speed from 1800 – 4000 1/min
- Field of application up to 6 m under water
- Increase of the electrode life
- Abrasion control with automatic electrode adjustment
- Feed control for safe and high-performance cutting
- Development of a automatic electrode change system
- Development of a hydrodynamic protection shield, to reduce water pollution by selective extraction of aerosol and particles
- Marked increase of the drive power
- Optimization of the current conductive module in terms of power density and safety

For cutting thick-walled structures with a CAMG system, it is necessary to use electrodes with a corresponding diameter. For using the system with handling systems, it is necessary to create a tool as small and as light as possible. The exponential increase of the drive power with increased electrode diameter is contrary to this aim; therefore, it is necessary to optimize the electrode radius. To enable this, the diameter of the work spindle, the current conduction module and the automatic electrode change system have to be as small as possible. Furthermore, the specific power (kW/kg) of the driving motor must be as high as possible. Up to now, the focus is to develop a concept that best integrates these conflicting aims.

The preliminary tests showed that the surface speed must be 35 – 40 m/s for electrode erosion to be kept within limits. A further reduction of the contact time between the electrode and arc at a higher surface speed does not reduce the electrode erosion significantly. An electrode with a diameter of 450 mm and a surface speed of 40 m/s uses a drive power of 30 kW. A hydraulic motor for powering the electrode, such as the existing CAMG system at the Materials Science of the University of Hanover, will be used because the power density of hydraulic motors is (in comparison to electric motors) very high. To prevent hydraulic oil contamination of the reactor water basin, in this project, a water hydraulic motor will be used (Figure 4).



Weights: 55 kg
Blade speed: 500 – 1800 rpm
Blade diameter: < 450 mm
Current: < 6000 A
Voltage: < 52 V

Fig. 4. Design engineering (left) and cutting tool (right) for CAMG

To use the advantage of high cutting rates, the set up time for changing the electrode has to be short. This is only possible, if electrode adjustment is automatic. Because of the required small spindle diameter, normal tension spindle systems (for example those used for milling machines) cannot be used, because they are too large and not qualified to conduct the load current of 6000 Amp. For this reason a special spindle system was designed . In qualification trials with the system shown in figure 4, plate thicknesses of up to 100 mm stainless steel could be cut in one operation, along with complex geometries like material knots. Additionally, the wear of the electrode could be reduced to < 2% by using special electrode geometries in combination with sintered materials.

CONCLUSIONS

For dismantling and decontamination tasks many state-of-the-art processes are available. Most are adapted to the special conditions of dismantling nuclear facilities, for example, plasma arc cutting under water. At the Institute of Materials Science in Hanover, additional new processes are under development such as the contact arc metal cutting / grinding process for dismantling and the dry ice laser beam process for decontamination tasks. High cutting speeds, even for complex metal parts, are achievable to cutting depths of more than 100mm for the contact arc metal grinding process. Even higher cutting thickness at reduced speeds can be attained by the contact arc metal cutting process. The dry ice laser beam process removes coatings like powder or decontamination coatings and layers of solid material like concrete or ceramic tiles. The main advantage of this process for decontamination tasks is that no secondary waste is generated.

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