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Automated Robotic Grinding of the Control Rod Drive Mechanism J-Groove Weld at PWR Nuclear Power Plants

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Abstract

Recent discovery of a cracked and leaking Reactor Pressure Vessel Head (RPVH) nozzles have raised concerns about the structural integrity of RPVH nozzles in the pressurized water reactor (PWR) nuclear power plants. In order to remove crack abnormalities in the areas of nozzle J-Groove Weld on reactor pressure vessel head, we have developed an "Automated Robotic Grinding" (ARG) system which removes the surface cracks of the J-Groove Weld nozzles. Cracks are removed by the means of grinding of the J-Groove Weld performed both automatically and remotely. A manipulator was designed to be attached to the nozzle of the reactor head and enable the grinder tool to move according to cylindrical coordinate system with three degrees of freedom. Control system allows a synchronized motion of the manipulator axes and remote operation of the ARG manipulator. The inputs for grinding are the surface area coordinates of the crack and the maximum depth of the crack. Due to the limited accessibility in the area around the CRDM nozzle, the system is designed to include combined sensor and actuator. The grinder tool is first used as a sensor in a procedure to automatically detect the surface topology in the given area of the J-Groove Weld and then as an actuator which grinds with predefined depth, leaving the surface smooth and free of sharp edges. In this paper we present main features of the ARG system as well as main features of the grinding procedure.

1. Introduction

The reactor pressure vessel head (RPVH) of Pressurized Water Reactors (PWR) is an integral part of the reactor coolant pressure boundary. The RPVH has penetration nozzles for instrumentation systems and Control Rod Drive Mechanisms (CRDM). A typical configuration of the reactor vessel head penetration nozzles is shown in Figure 1. It is used in most of the PWR power plants worldwide. Penetration nozzle made of Alloy 600 is fitted into the vessel head made of the low alloy steel. The joint between the RPV head and the penetration nozzle is achieved by the so called J-Groove weld [1]. It ensures the mechanical fixture and sealing of the pressure boundary.

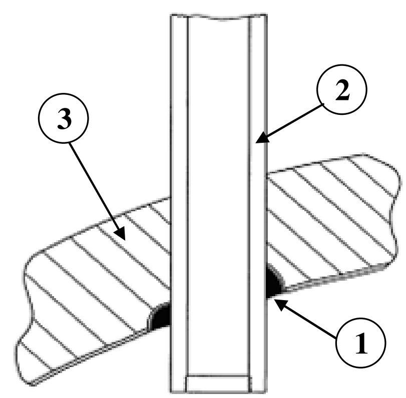

Figure 1: Typical CRDM Nozzle penetration. 1 – J-Weld region, 2 – RPVH nozzle, 3 – RPVH cladding

Operating conditions of PWR plants and primary coolant water, particularly the temperature and operation time of the reactor, can cause cracking of these nickel-based alloys. This is a potential safety concern because a nozzle with a wide cracking could break off during operation, compromising the integrity of the reactor coolant system pressure boundary.

The discovery of leaks and nozzle cracking at various power plants has made clear the need for more effective inspections of RPV heads and associated penetration nozzles [2-4], where the cracks of the J-Groove Weld are discovered and repaired.

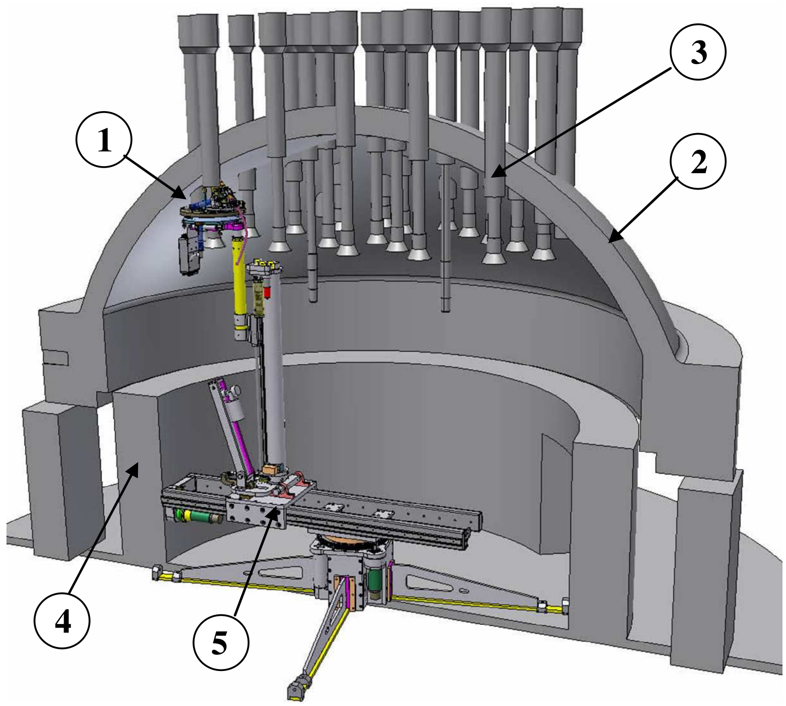

Figure 2: RPVH inspection area and positioning of the ARG manipulator on a nozzle penetration of the reactor pressure vessel head. 1 – ARG manipulator, 2 – RPVH cladding, 3 – CRDM nozzle penetration, 4 – RPV head is placed on a examination stand during the inspection, 5 – LIN Manipulator used for remote positioning of the ARG manipulator module on a nozzle penetration

One of the possible solutions for crack removal is boring out and re-welding the original J-groove weld and the lower part of the nozzle containing the cracks [5]. However this procedure is both time consuming and expensive, prolonging the downtime of the powerplant [9].

In order to repair the cracks of the reactor nozzles within the time constraints of the scheduled power plant inspection when the power plant is already not operational, we have developed a novel system which is capable of removing the cracks in the J-weld region by means of grinding the surface of the nozzle penetration J-weld. In this manner propagation of the surface crack is prevented or slowed.

In this article we present overall overview of the “Automated Robotic Grinding” (ARG) system along with the grinding procedure.

2. Overview of the ARG system

Grinding is performed with a grinder tool powered remotely via flexible shaft. The grinding tool is ball shaped and 8mm in diameter. When powered, the grinding tool head rotates and if pressed against the surface it removes the material from the surface.

In order to enable remote operation and precise positioning of the grinding head tool around the nozzle penetration, we have designed the ARG manipulator which is attached to the nozzle penetration, holds the grinding tool and is able to manipulate the grinding head tool with three degrees of freedom.

Figure 2 provides an overview of the ARG manipulator positioning on an arbitrary CRDM Nozzle. ARG manipulator is mounted as an end effector to the existing manipulator used for manipulation of the inspection equipment in the area under the reactor vessel head. This manipulator, called LIN Manipulator, is used for remote positioning of the ARG manipulator on a desired CRDM Nozzle. The description of the LIN Manipulator and operation of equipment and end effectors in the inspection area is beyond the scope of this paper, however additional information can be found in [6].

2.1. ARG manipulator

As can be observed on the Figure 3, ARG manipulator has three axes of movement which ensure the position and remote drive of the grinding tool head. C-axis is rotational and it is used to position the grinding head around the nozzle. Linear X-axis is used for radial positioning of the grinding tool head in respect to the penetration. Z-axis positions the grinding tool head by height (measured from penetration's bottom surface).

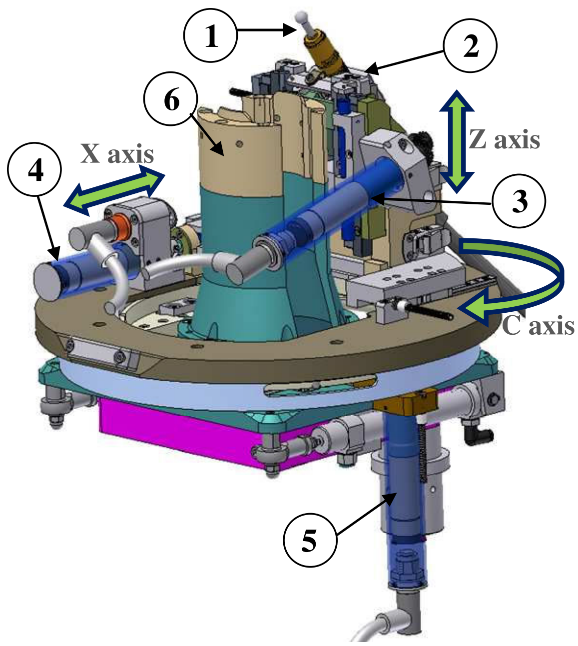

Figure 3: ARG Manipulator overview. Mechanical components: 1 - the grinding head tool, 2- holder for the grinding tool, 3 - Z axis motor (height positioning), 4 - X axis motor (radial positioning), 5 - C axis motor (rotation positioning), 6 - centering and fixing system used to attach to the CRDM Nozzle

Holder for the grinding head tool is fixed on the ARG module on the top of the Z axis. The grinding head tool is coupled to the Z axis by a spring. This provides passive compliance of the grinding head, absorbing vibrations of the grinding head tool when grinding the surface and provides shock robustness to possible impacts that would normally damage the axis positioning mechanisms.

While working, ARG module is monitored with several cameras. Camera mounted on the ARG module is used for monitoring of the grinding tool head. The other cameras under RPVH also monitor the work of the ARG module.

2.2. ARG control system

It is very difficult to approach the area of the J- weld region of the CRDM nozzle. Due to the high radiation level under the reactor vessel head, it is mandatory to have a remote control and operation of the ARG manipulator. It was important to design a control system architecture that will enable a simple teleoperated manipulation.

We have designed the control system in two stages, distributing the workload between the low level control system (LLCS) and high level software running on a PC (see Figure 4). Low level control system was designed to run all of the time critical operations including motion control, sensor reading and safety procedures if any of the manipulator working parameters comes into an undesired range, which could lead to damaging the reactor vessel head. High level software running on the PC was used to process the commands of the operator and process mathematical algorithms for surface topology detection and offline trajectory verification of the manipulator axes.

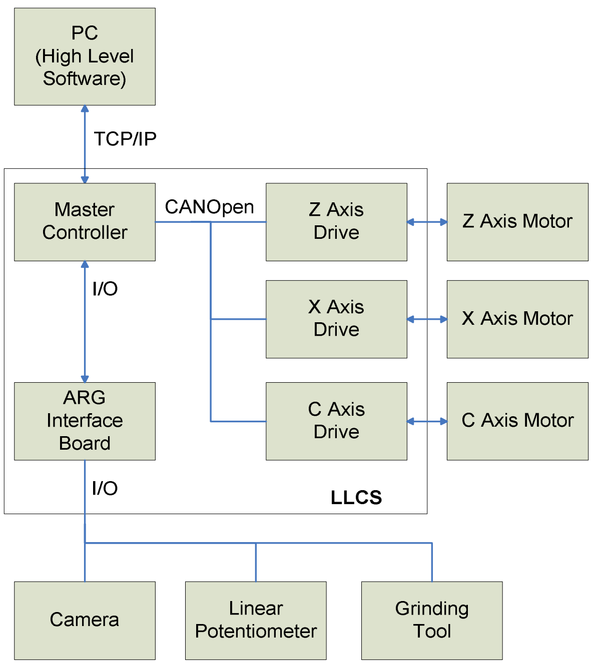

Figure 4: ARG control system architecture overview. PC is connected to the Master Controller which is placed inside a control box together with the other components of the LLCS. Each motor is controlled by its separate motor drive connected with the other drives and the Master Controller through CAN connection using the CANOpen network [10]. In this manner the Master Controller also has a role of a multi-axis controller and controls the synchronized axes movement during the grinding. Specially designed ARG Interface Board is used as an interface between the Master Controller and Linear Potentiometer measurement, Grinding Tool control, and control of the Camera which is mounted on the ARG manipulator.

Components of the LLCS are placed in a custom designed box, outside of the reactor vessel head inspection area. In order to achieve a high precision of the ARG manipulator and arbitrary grinding head tool manipulation, distributed motion control architecture is utilized. Each of the axis motors is driven with a separate digital motor drive responsible for servo loops (position, velocity, current) execution [11]. A multi-axis motion controller was used to enable motion control synchronization and trajectory manipulation of the manipulator axes.

High level software running on a PC placed in the area with no radiation ensures a safe teleoperated manipulation of the ARG manipulator. The PC is connected to the LLCS through Ethernet connection using the TCP/IP protocol.

3. The grinding procedure

The grinding procedure is organised in three stages: definition of the grinding area, surface topology detection and calculation of the grinding path and grinding.

In the first stage the area for grinding is determined. This is done before the deployment of the ARG system following the results of the J-Groove Weld inspection using the Eddy Current methods.

The second stage is surface topology detection. Its purpose is to find the position of the manipulator axes in the given area, where the grinding head tool will slightly touch the surface of the material. Knowing these positions a grinding path of the manipulator axes is calculated.

The third stage is grinding. The grinding head tool is powered and by moving the grinding head tool along the grinding path, a desired portion of the surface material is removed.

The same tool is used for detection of the surface topology and for removal of the material. This simplified the operation of the ARG manipulator reducing its size and cost, not hindering the overall performace of the system. Due to the complex geometry of the treated surfaces, irregular shape of the nozzle penetrations and surface imperfections of the welded area, the precision of the ARG tool and detection of the surface topology are crucial. Because of this, it has been given a special consideration.

3.1. Definition of the grinding area

In the case if the crack has been discovered by examination of the nozzle penetration J-Weld area using the Eddy Current methods [7], one has to decide if the crack can be removed using the ARG system. The size of the grinding area is then determined depending on the shape, size and depth of the crack.

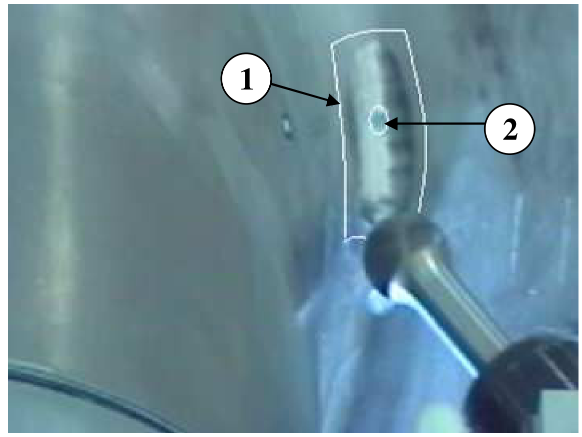

Figure 5: Definition of the grinding area on a mockup CRDM nozzle in the Inetec laboratory. 1 – The grinding area where the grinding tool removes the material, 2 – The surface crack

The figure 5 displays the definition of the area designated for grinding. It can be observed that the grinding surface encompasses a larger area of the material than the crack itself. This is due to the need for removing the crack and leaving the surface smooth and free of sharp edges.

In addition, based on these dimensions, a grid of uniformly distributed points which represent discretization of the grinding surface is created. The grid is defined with the coordinates of two manipulator axes (e.g. X - radial and C - angular position). Hence, the grinding surface mesh is defined by the Z axis coordinate above a grid in the C-X horizontal plane. Thereby the problem of the surface topology detection is reduced to obtaining the value of Z axis position for each point in the grid at which the grinding head tool will touch the surface material.

3.2. Detection of the surface topology

The detection of the surface topology was accomplished by measurement of the spring deflection using a potentiometer (Figure 6). Grinding tool holder is mounted on a linear slide guide. The spring holds movable part of the linear slide guide in reference position. The potentiometer shaft is also connected to the movable part and measures its movement (and thus spring deflection). When pressing the surface with the grinding head, the spring would compress and by observing the difference of the potentiometer reading we were able to detect the contact of the grinding head and the surface of the material.

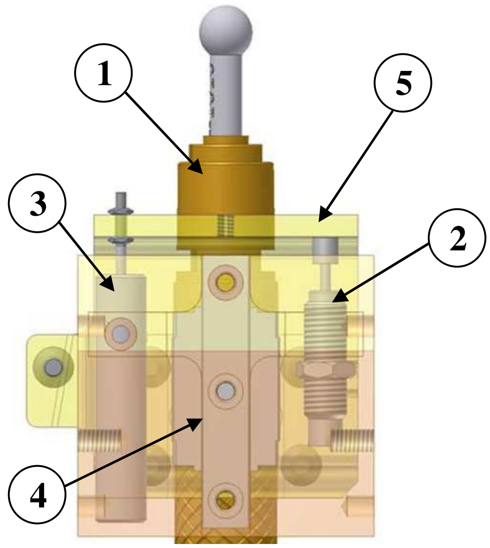

Figure 6: Mechanical assembly of the grinding tool mounting construction. 1 – Grinding tool, 2 – Spring, 3 – Linear potentiometer, 4 – Linear slide guide, 5 – Grinding tool holder.

We have developed a probing procedure to have an automated detection of surface topology for all of the points in the grid. The ARG manipulator is positioned in the area where the grinding head is not touching the material. Two axes (e.g. axis C-rotational positioning and axis X-radial positioning) are held in the position defined by the coordinates of the grid point and the third axis, used for probing, moves toward the surface of the reactor head (e.g. axis Z-height positioning).

Potentiometer reading is sampled during the motion of the manipulator axis at a rate of 1 kHz. When a change of the potentiometer reading, matching 0.3% change of the whole potentiometer range is detected, the axis is stopped. This indicates the contact of the grinding head tool and the surface of the material. The Z axis surface coordinate is calculated based on the position of the axis and the measurement of the spring deflection. The procedure is then repeated for the other grid points.

3.3. Calculation of the grinding path

After the surface topology of the material is obtained, it is necessary to define the grinding path for the manipulator axes, where the grinding head will press the surface of the nozzle penetration weld and with a grinding tool powered, remove a desired portion of the welded material.

This is accomplished by creating a desired shape of the surface and defining a path of the manipulator axes along the coordinates of this new surface. We have defined an amount and shape of the material which needs to be removed in a form of a mathematical function. By adding the value of this function to the measured values of the initial material surface points obtained in the process of surface topology detection, we have created the desired shape of the material after the grinding. The function parameters are the coordinates of the grinding area grid and the maximum depth of grinding.

In a case when the grinding area is defined in the C-X plane and the height of the material is probed, a grinding function:

$$Z = f_g\,(X, C, d_{max}),$$

which describes a desired shape of the removed material is calculated. Grinding function is chosen to suit for several requirements. Function is defined on a rectangular area with a smooth ending for every point on the edge of the area, ensuring a smooth transition between the grinded and non grinded surface. It has a smooth peak in the central point, so that the maximum grinding depth is in the middle of the grinding area, where the crack is located. Function is also symmetrical along both axes in regard to the central point. An example of the grinding function can be seen in Figure 7.

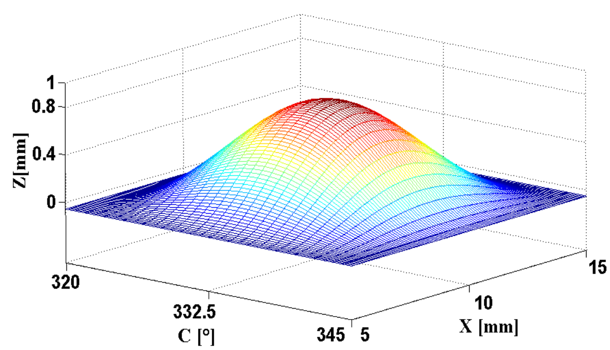

Figure 7: The example of the grinding function defined on area with X axis coordinates ranging from 5mm to 15mm, and C axis from 320° to 345°. The central point of the function located at 10mm and 332.5° defines the highest depth for grinding of 0.8mm.

The Figure 8 shows an overlay of the initial surface of the material and grinding surface calculated by adding the value of the grinding function to each measured point.

When grinding, the manipulator axes move along the coordinates of the grinding surface with grinding head tool powered. The grinding starts at the edge point of the grinding area. The trajectory is defined such that the grinding head tool moves around the nozzle penetration removing more material in each pass.

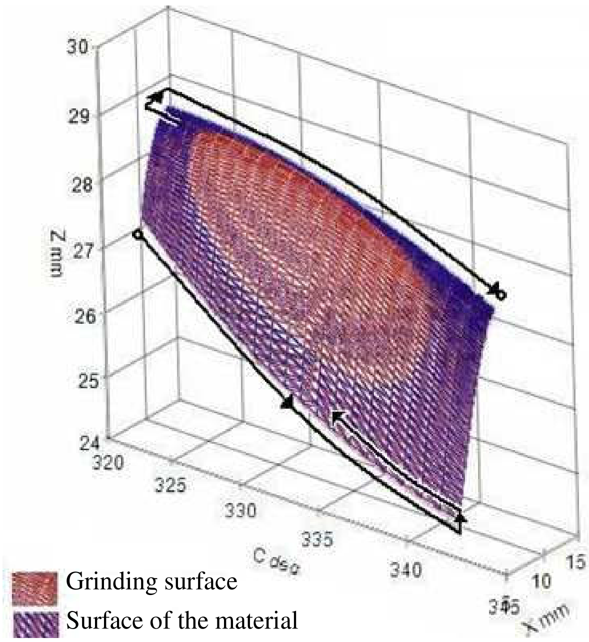

Figure 8: The grinding area as viewed in the ARG software after the detection of the surface topology (blue) and calculation of the grinding surface (red). The black lines sketch the grinding path of the grinding head tool

4. Dimensional control results

In order to evaluate the described method of grinding and test the overall performance of the ARG system, the system was tested in a laboratory on a mockup nozzle penetration. The mockup of the nozzle penetration had several cylindrically shaped cracks with diameter of 2mm and depth of 0.5mm. The ARG manipulator was attached to the penetration and one of the cracks removed using the described procedure of grinding. The grinding surface and maximum grinding depth were defined as observed in the Figure 5, Figure 7 and Figure 8.

The dimensional control of the mockup penetration before and after the removal of the crack has been performed using the digital photogrammetry method [8]. This yields a 3D model of the mockup penetration giving a relation of the penetration surface before and after the grinding. Several cross-cut planes (see Figure 9) of the mockup penetration around the crack area before and after the grinding have been analyzed.

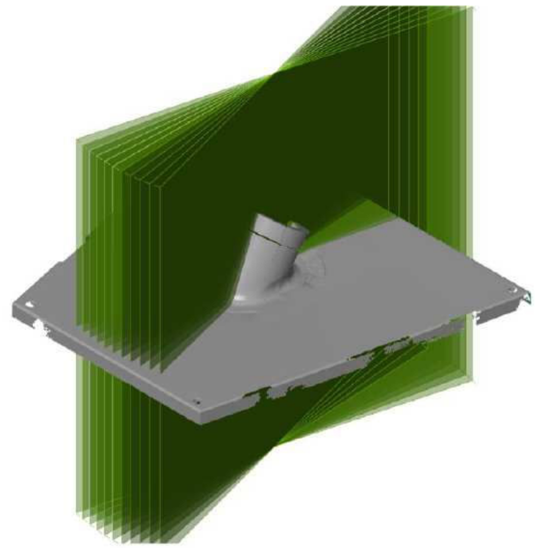

Figure 9: The cross-cut planes of the mockup nozzle penetration.

In this manner we were able to measure the grinded depth and evaluate the shape of the grinded area after the surface treatment. Figure 10 displays the cross-cut plane of the penetration surface which is going through the centre of the crack.

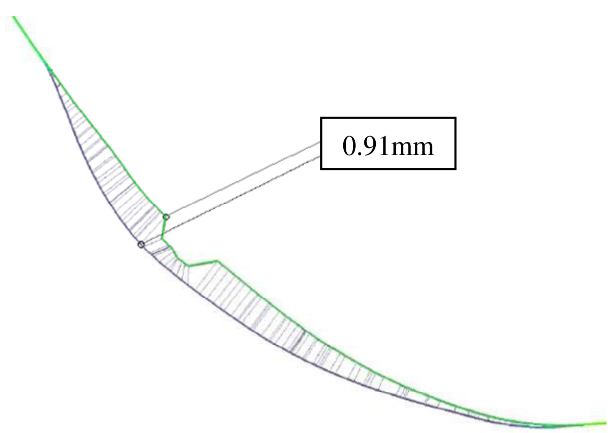

Figure 10: Cross-cut surface of the mockup penetration taken in the centre of the crack showing the surface before (green line) and after the grinding (blue line) and maximum grinded depth of 0.91mm

It can be observed that the surface is left smooth after the grinding and the crack has been removed.

5. Conclusions

This paper has presented a novel system developed for automated removal of surface cracks in the J-Groove weld area of nuclear reactor pressure vesel head nozzles at PWR power plants. The system is designed to automatically detect the surface topology in the area where the crack has been located and remove a desired portion of the surface material based on the size, shape and depth of the discovered crack.

In addition, the method and the overall concept of the crack removal described in this paper is generic and can be used for material removal when the grinding tool mobility and accessibility is limited by spacial contraints and the exact position of the surface material is unknown.

The performance demonstration of the ARG system on a specially designed mockup nozzle penetrations with artificial cracks in the J-Groove weld area shows that selected and designed equipment along with the proposed procedure is capable to successfully remove surface cracks.

The dimensional control results performed on a mockup nozzle penetration showed a 0.11mm deviation from the desired maximum grinding depth, that a future work will try to improve. Future efforts will be addressed to further improvement of the ARG system accuracy and a more flexible definition of the grinding surface.

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