Comparative study on the processing of armour steels with various unconventional technologies

E Herghelegiu, C Schnakovszky, M C Radu, N C Tampu and V Zichil
Vasile Alecandri University of Bacau, Calea Marasesti 157, 600115, Bacau, Romania

E-mail: eugen.herghelegiu@ub.ro

Abstract. The aim of the current paper is to analyse the suitability of three unconventional technologies - abrasive water jet (AWJ), plasma and laser – to process armour steels. In view of this, two materials (Ramor 400 and Ramor 550) were selected to carry out the experimental tests and the quality of cuts was quantified by considering the following characteristics: width of the processed surface at the jet inlet (Li), width of the processed surface at the jet outlet (Lo), inclination angle (α), deviation from perpendicularity (u), surface roughness (Ra) and surface hardness. It was found that in terms of cut quality and environmental impact, the best results are offered by abrasive water jet technology. However, it has the lowest productivity comparing to the other two technologies.

1. Introduction

The materials used for armour manufacturing are difficult to process by conventional technologies due to their special properties. To overcome this problem, different unconventional technologies, widely used in industry, were tested, as plasma or laser processing, abrasive water jet machining etc.

Plasma processing is an unconventional technological process that is used for conductor of electricity materials as steel, stainless steel, aluminium and aluminium alloy, bronze, etc. By using CNC machines and different gases (as oxygen, nitrogen, hydrogen, argon), plasma cutting allows obtaining very complex 2D and 3D shapes [1, 2]. Its main advantages consists in high productivity, the possibility to cut thick materials (up to 150mm) and low processing cost compared to other unconventional methods presented in this article.

Laser machining is the process of material removal by means of a laser beam. It is based on photon energy in the form of heat or by means of gas (nitrogen, oxygen, argon, etc.) which removes material by melting or evaporation. There is a large range of processes based on laser technology (cutting, engraving, drilling, welding, different heat treatments), that can be used for a large variety of materials as metal, ceramic, glass, plastics, composite materials, etc. The main advantages of laser machining are the high processing speed, high dimensional accuracy and the possibility to obtain very complex 2D or 3D shapes. The disadvantages are related to the high cost of machining, the thermally damaged machined surface which involve further processing to remove the affected layer via a classic process as turning, milling, grinding.

Abrasive water jet machining (AWJ) is an unconventional technology which has greatly developed in recent decades, being used in many industries (automotive, aerospace, etc.) to process various materials as steel, stainless steel, aluminium alloys, bronze alloys, granite, marble, plastic, glass, wood, etc. It is an environment friendly process (it does not release chemical compounds or dust that harm the environment or the operator), it does not degrade thermally the processed surface, it can...
process various complex shapes using the CNC equipment, it is easy to program etc. The disadvantages of water jet processing are the high cost of equipment and spare parts, the impossibility to processes parts in package, low productivity, low thickness of parts to be processed (greater thicknesses lead to ridges occurrence on the processed surface and sloping angle of cut). The aim of the current paper is to analyse the suitability of the above mentioned unconventional technologies to process armour steels.

2. Experimental methodology
The experimental tests were performed on Ramor 400 and Ramor 500 high-strength steel metal sheets, using the following equipment: MAXIEM 0707 machine for abrasive water jet processing, OXYTOME.B 25E machine for plasma processing and TRUMPF 3030 for laser processing. The two materials are usually used in the manufacturing industry of maximum safety equipment, especially in building of armoured cars. Their chemical composition and mechanical properties are presented in table 1 and table 2, respectively.

Table 1. Chemical composition of materials [3, 4].

| Material | Chemical composition (max %) |
|----------|------------------------------|
| Ramor 400 C | 0.24 | Si | 0.70 | Mn | 1.50 | Cr | 1.00 | Ni | 1.00 | B | 0.005 |
| Ramor 550 C | 0.36 | Si | 0.60 | Mn | 1.00 | P | 0.012 | S | 0.003 | Al | 0.060 | Cu | 0.30 | Cr | 1.50 | Ni | 2.50 | B | 0.005 |

Table 2. Mechanical properties of materials [3, 4].

| Material | Thickness (mm) | Yield strength (MPa) | Ultimate strength (MPa) | Hardness (HB) | Elongation A5min (%) | Resilience (Joule) |
|----------|----------------|---------------------|------------------------|--------------|----------------------|--------------------|
| Ramor 400 | 6.5 | 1100 | 1300 | 360-450 | 8 | 20 |
| Ramor 550 | 6.5 | 1550 | 1850 | 540-600 | 7 | 16 |

The experimental tests were performed using the optimum working parameters that the used machines have been able to provide. Thus, the working parameters used in AWJ processing of the two materials were: water jet pressure of 300MPa, feed rate of 80 mm/min, abrasive material quantity of 500 g/min, distance between the cutting head and metal plates of 2 mm, focus tube length of 102 mm, focus tube diameter of 0.74 mm; the abrasive material was Granat #80.

In case of plasma processing with the above mentioned machine, the cutting parameters are preset as a function of the used material and its thickness so that they cannot be varied; therefore, the cutting parameters used during the current experiments were: feed rate of 150 cm/min, cut thickness of 1.8 mm, plasma arc voltage of 130 V, argon pressure of 1.6 bar and oxygen pressure of 5.5 bar.

In case of laser cutting, the working parameters were: power of 3200 W, frequency of 20000 Hz, feed rate of 2 m/min, distance between the laser head and metal sheet of 1.3 mm, gas pressure of 0.8 bar (the used gas was oxygen).

To quantify the quality of cuts performed by the three unconventional technologies, six parameters were analysed (fig. 1): width of the processed surface at the jet inlet (Li), width of the processed surface at the jet outlet (Lo), inclination angle (α), deviation from perpendicularity (u), surface roughness (Ra) and surface hardness.
The experimental measurements were done by using the following devices: Leica MZ75 microscope for measuring the Lo, Li, u and α parameters, Mitutoyo SJ 201 roughness device for roughness and ULTRAMATIC 2 ultrasound hardness device for surface hardness measurement.

![Image](image.jpg)

**Figure 1.** Parameters used to quantify the quality of cut processed by AWJ [5, 6].

### 3. Results and discussions

The results obtained after performing the experiments are shown in figure 2 and table 3 respectively (both, as values of the measured parameters and as images of the cut sections for the two materials processed by each technology). The variation of width of the processed surface at the jet inlet (Li) as a function of the applied technology, for both materials, is presented in figure 3a. It can be observed that the lowest value of the Li parameter resulted in case of laser processing and the highest value in case of plasma processing. Abrasive water jet processing led to similar results for the Li parameter, independent of the used material.

The influence of processing technology on the width of the processed surface at the jet outlet (Lo) is presented in figure 3b. The lowest value of the Lo parameter was obtained in case of processing the RAMOR 550 steel by laser. Plasma processing led to the highest values for the Lo, with a slightly difference between the two materials. The abrasive water jet processing influences this parameter, but independent of the processed material.

The deviation from perpendicularity (u) resulted from each technology is presented in figure 3c. Again the lowest value was obtained in case of laser processing and the highest value in case of plasma processing. This time, the abrasive water jet processing led to different results for the two materials. The difference is more accentuated in case of plasma processing.

The variation of the inclination angle (α) as a function of the processing technology is shown in figure 3d. It can be seen that plasma processing led to inclination of cuts up to 3.5° while laser processing led to inclination angles up to 0.6°. Abrasive water jet processing determined inclination angles of the processed surface up to 1.3°. For all the three technologies, the differences are small between the two materials.
Figure 2. Parameters that quantify the quality of surfaces cut by different unconventional technologies.

The variation of surface roughness (Ra) as a function of the applied technology is presented in figure 3e. It can be seen that a rough surface was obtained in case of plasma processing comparing to the other two technologies. The roughness of the RAMOR 550 steel resulted smaller for all the three technologies comparing with that of RAMOR 400 steel.
Table 3. Experimental results.

| Parameter | Laser Ramor 400 | Laser Ramor 550 | Plasma Ramor 400 | Plasma Ramor 550 | AWJ Ramor 400 | AWJ Ramor 550 |
|-----------|-----------------|-----------------|-----------------|-----------------|--------------|--------------|
| Li (mm)   | 0.67            | 0.53            | 1.96            | 1.88            | 0.79         | 0.78         |
| Lo (mm)   | 0.52            | 0.4             | 1.23            | 1.15            | 0.5          | 0.5          |
| u (mm)    | 0.08            | 0.06            | 0.56            | 0.37            | 0.15         | 0.12         |
| α (°)     | 0.62            | 0.43            | 3.58            | 3.47            | 1.33         | 1.14         |
| Ra        | 3.43            | 2.25            | 13.33           | 12.8            | 4.09         | 2.47         |
| HV        | 423.7           | 590             | 406.6           | 537             | 340          | 437          |
| Cut section | ![Images](image1.png) | ![Images](image2.png) | ![Images](image3.png) | ![Images](image4.png) | ![Images](image5.png) | ![Images](image6.png) |

The surface hardness modified as results of processing by the three unconventional technologies (figure 3): in case of plasma and laser processing an increase of hardness (especially for RAMOR 550 steel) resulted while in case of abrasive water jet cutting the surface hardness slowly decreased.

Figure 3. Surface hardness as a function of the applied technology.

The surfaces’ macrostructure obtained after abrasive water jet, laser and plasma processing are presented in figure 4. It can be observed that in case of abrasive water jet cutting, some striations are presented at the bottom of surface, they being more pronounced at Ramor 400 steel; otherwise the surface shows micro-pinches caused by the erosive action of abrasive material. The surfaces resulted after laser processing present three zones: one at the jet inlet, where some small striations can be observed (more pronounced in case of Ramor 400 steel), followed by a smooth surface (which is narrower in case of Ramor 400 steel) and again a zone with larger striations, at the jet outlet (smoother in case of Ramor 550 steel). The surface processed by plasma technology shows striations over the entire section with deposition of molten material at the jet outlet (figure 5).
Figure 4. Macrostructures of surfaces processed by abrasive water jet, laser and plasma.

4. Conclusions
Three unconventional technologies – abrasive water jet, laser and plasma – were tested to analyse their suitability to process armour steels, taking into account the following quality characteristics: width of the processed surface at the jet inlet (Li), width of the processed surface at the jet outlet (Lo), inclination angle (α), deviation from perpendicularity (u), surface roughness (Ra) and surface hardness.

The experimental results revealed that in terms of cut geometry (Li, Lo, α, u) and surface roughness (Ra), the best results were obtained from laser processing and the worst results from plasma processing. Abrasive water jet processing led to results closer to laser processing. However, taking into account the surface macrostructure, abrasive water jet technology allow obtaining the best cuts (striations occurred only at the bottom of cut, any molten material). Besides, this technology is environmental friendly. Its disadvantage is the low processing speed so that one has to put in balance the quality aspects and the productivity when has to choose the technology for a given part.

Figure 5. Surfaces resulted after plasma processing: a. Ramor 400, b. Ramor 550.

5. Acknowledgement
This study was performed through Partnership program in the PN II priority areas, developed with MEN-UEFISCDI (Romanian National Authority for Scientific Research) support, project no. 294/2014.

6. References
[1] Nemchinsky V A, Severance WS 2009 J. Phys. D. Appl. Phys. 42 195
[2] Colombo V, Concetti A, Ghedini E, Rotundo F, Sanibondi P, Boselli M, Dallavalle S, Gherardi M, Nemchinsky V, Vancini M 2010 Plasma Chem. Plasma Process, 32 411
[3] *** https://www.ssab.com/products/brands/armox/ramor-400, accessed 30.03.2017
[4] *** https://www.ssab.com/products/brands/armox/ramor-550, accessed 30.03.2017
[5] Herghelegiu E, Radu C, Schnakovszky C and Zichil V 2015 App. Mech. Mat. 809-810 207
[6] *** ISO/ WD/ TC 44 N 1770 - 2010.