საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 19(193), №2, 2025
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 19(193), no. 2, 2025

Materials Science

Development of Plasma Cutting Technology for High-Strength Composite Materials in the Environments of Compressed Air and Superheated Water Vapor

Zurab Sabashvili[*], Grigor Tatishvili[**], Tamar Loladze[*], Gela Otarashvili[*], Nino Kenchiashvili[*], Marina Kapanadze[*]

[*] *Faculty of Chemical Technologies and Meteorology, Georgian Technical University, Tbilisi, Georgia*
[**] *Academy Member, Georgian National Academy of Sciences; R. Agladze Institute of Inorganic Chemistry and Electrochemistry, Tbilisi, Georgia*

Abstract. High-strength, highly modular polymeric fibers are commonly used to produce materials with high toughness and impact strength at low densities. One such material is a high-strength composite made of aramid fibers, which is used for making armour. The challenge lies in machining these materials. The low resistance of the cutting tool can lead to the separation of material layers, fiber tearing, and temperature increases in the cutting area, resulting in thermal destruction of the matrix. To address this, plasma arc-cutting technology was developed to avoid splitting and destruction of the material. The material was secured between two water-cooled copper plates, and a water jet was sprayed into the cutting area. This ensured that the cutting surface remained monolithic, easily machined, and free from destruction. Studies were conducted for both air plasma arc cutting and cutting in superheated water vapour. © *2025 Bull. Georg. Natl. Acad. Sci.*

Keywords: aramid fibers, plasma cutting, superheated water vapor, cutting speed, arc power, nozzle

Introduction

Modern industries widely use high-strength non-metallic fiber composite materials. These materials consist of two or more components combined into a single monolithic structure, whose physical and mechanical properties differ from those of each constituent component. High-strength, highly modular polymeric fibers are used to produce these materials, ensuring toughness and impact strength at low density.

Mechanical processing of such materials is common in production. However, this treatment often results in low performance and, in many cases, destruction of the material.

The research goal was to develop and explore plasma cutting techniques for high-strength aramid fiber composites. Para-aramids, also known as "Kevlar" and developed by DuPont, are used for manufacturing armored products, such as body armour. The material withstands temperatures up to 430°C, but begins to break down above this temperature. Prolonged exposure to ultraviolet rays and moisture can degrade the material properties. Para-aramids are characterized by low density, high mechanical and thermal strength, and tear strength ranging from 2800 N/mm² to 5500 N/mm², depending on the manufacturing brand.

The decomposition temperature of the material depends on the heating rate and the duration of exposure to heat. At temperatures above 150°C, the strength of Kevlar decreases; for instance, at 160°C for over 500 hours, the tensile strength decreases by 10-20%, and at 250°C, Kevlar loses 50% of its strength in 70 hours [1-3]. Additionally, aramids are easily flammable. The main goal was to solve the aforementioned problems when developing the plasma arc cutting technology.

Methodology

During the development of plasma cutting technology for high-strength non-metallic fiber-reinforced composite materials, a power source and an indirect plasma torch were designed based on the thermophysical properties of the material. The electrical parameters of the power source were measured using an analogue ammeter (85C1-A) with a measurement range of 0-300 A, and a digital voltmeter (D69-230) with a measurement range of 0-500 V.

For the experiments focused on developing the technology for measuring pressure and flow rate of plasma-forming media, mechanical manometers (PG-L-08, accuracy class 1.6) and flow meters (RS-5 and RM-4) were used. Mercury thermometers were employed to measure the temperature of water vapor at the entrance to the plasma torch.

Results and Discussion

At the initial stage of the experiment, the drawbacks of mechanical cutting for high-strength fibrous composite materials made of Kevlar were confirmed. During mechanical cutting, the following shortcomings were revealed: poor productivity; high cost associated with frequent failure of mechanical cutting tools; destruction of the cutting surface; breakage of the surface film of a workpiece causing damage to the monolith resulting in a loss of its properties.

To develop plasma arc cutting technology, the problem of burning aramid fibers in oxygen needed to be solved. References indicate that at low concentrations of oxygen, fiber burning occurs briefly, and the flame dies quickly. On the one hand, it might be possible to solve the problem by selecting a plasma-forming environment that does not contain oxygen. However, from an economic point of view, using inert gases, for example, was unprofitable. Therefore, the first cycle of the study was conducted using compressed air, and the second cycle using water vapor. Fiber burning was observed in both cycles.

For plasma arc cutting in compressed air, an indirect plasma torch with a plasma arc of 10 kW was used. The technical parameters of the power supply are provided in Table 1.

Table 1. Power supply electrical parameters

Parameters	Magnitude
No-load voltage, U_{xx},V	360
Nominal operating voltage, U, V	220
Nominal operating current, I, A	45
Power consumption from the electrical network, kVA	16.2

During the first cycle of experiments, it was found that at the maximum cutting speed, the plasma arc flame was sucked into the cutting cavity, which contributed to the burning of fibers. The burning process lasted for a few seconds, but even in such a short period, it caused an increase in the cutting width, the detachment of material layers, and the tearing of fibers. The sucking of the flame into the cutting cavity at maximum speed can be explained by the small angle (30°) between the flame and the workpiece surface. During the experiments, it was determined that at an angle of 90°, no flame was sucked into the cutting cavity.

Since the material loses its mechanical properties when heated to temperatures above

250°C and its layers tend to separate, it is essential to prevent overheating near the cutting zone. The solution to these problems is as follows: two copper plates, each 6 mm thick and 8 cm wide, were used. Their length matched the length of the workpiece. Grooves were cut along the entire length on one side of both plates to allow water to be supplied for cooling the workpiece's surface. To prevent delamination, the material was placed between the copper plates with the grooved sides facing the material and secured with mechanical clamps. Additionally, an extra stream of water was directed into the cutting cavity, completely preventing the ignition of the fibers.

In plasma arc cutting using the proposed technical solutions, the process is accompanied by the melting of the material. The cutting surface has a molten, monolithic appearance, which is easily machined, and no separation or destruction of the material occurs.

The second study cycle was conducted using superheated water vapor as a plasma-forming medium. Previous studies have shown the following advantages of using water vapor compared to compressed air [4], including: high plasma redox potential; higher values of thermophysical parameters create excellent conditions for converting arc electric energy into thermal energy and maximizing its usage; the increased electric field intensity of the plasma arc in the water vapor medium allows for the generation of the required arc power at a reduced current intensity compared to compressed air; the possibility of conducting the plasma cutting process at high pressure, which also allows for reducing arc current; the reduction in current value increases the service life of the cathode.

It is known that a plasma-forming gas layer of a certain thickness surrounds the arc, providing thermal insulation from the nozzle walls. In the case of water vapor, the dissociation of hydrogen consumes a large amount of heat, providing intensive cooling of the arc's periphery. Additionally, the presence of a radial velocity component in the gas flow, directed into the arc column, enhances thermal compression of the arc column. This intensifies the deionization of its peripheral region, contributing to the elongation of the arc and increasing the arc voltage. The increased arc voltage allows generating the required power at lower currents than with compressed air. Both the pressure and temperature of the plasma-forming medium influence the increase in voltage [5]. Superheated water vapor was used in the experiments because it contains no moisture. Moisture evaporates at temperatures above 125°C, and there is no condensation in the superheated vapor caused by the heated walls of the superheater tank.

Comparative studies were conducted for both plasma-forming environments. Table 2 shows the values of the main technological parameters.

Table 2. Technological parameters

Water vapour				Compressed air			
I,A	U,V	P,at	t°C	I,A	U,V	P,at	t°C
40	242	3	160	48	210	3	-
40	246	4	170	45	220	4	-
36	248	5	180	-	-	-	-
30	254	6	190	-	-	-	-

The data in Table 2 confirm the aforementioned advantages of water vapour. The plasma-cutting surface, in this case, also exhibited a molten monolithic appearance. The plasma cutting speed was nearly identical in both cases. Naturally, indirect plasma torches were used for plasma cutting. The optimal design was found to be a nozzle with a channel diameter of 2 mm and a height of 18 mm. Based on the accepted technological solutions, two designs of plasma cutting units were developed: one for compressed air and the other for superheated water vapor. For compressed air, the plasma torch is cooled by running water. At the inlet of the plasma torch, part of the water is supplied to the cutting cavity, while the rest is drained from the plasma torch into the copper plates. A valve is installed at the bottom of the bath to drain the water.

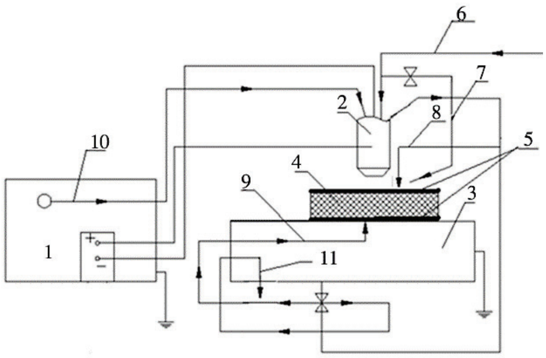

Fig. Communication connections scheme of a plasma cutting installation: 1. Power supply; 2. Plasma torch; 3. Bath; 4. Material to be cut; 5. Copper plates; 6. Communication for supplying cooling water to the plasma torch; 7. A stream of water fed into the cutting area; 8. & 9. Communication of water supply to copper plates; 10. Communication for supplying compressed air to the plasma torch.

In the case of superheated water vapor, the plasma torch is cooled with compressed air to prevent the cooling and condensation of vapor. Water is fed into the cutting cavity and copper plates from the central water supply.

Figure presents the system communication connection scheme, illustrating the developed technological solutions for compressed air.

Conclusion

The plasma arc cutting technology has been developed for non-metallic fibrous composite high-strength materials, particularly aramid fibers, in both compressed air and superheated water vapor environments. The electrical parameters of the power source are selected to ensure that, in addition to providing the required power for the plasma arc, the maximum working life of the plasma torch is achieved. The application of this technology eliminates the burning of fibers and produces a molten, monolithic cutting surface that is easily machined and not prone to destruction.

მასალათმცოდნეობა

მაღალმტკიცე კომპოზიციური მასალების პლაზმური ჭრის ტექნოლოგიის შემუშავება შეკუმშული ჰაერისა და გადახურებული წყლის ორთქლის გარემოში

ზ. საბაშვილი*, გ. ტატიშვილი, თ. ლოლაძე*, გ. ოთარაშვილი*, ნ. კენჭიაშვილი*, მ. კაპანაძე***

** საქართველოს ტექნიკური უნივერსიტეტი, ქიმიური ტექნოლოგიებისა და მეტეოროლოგიის ფაკულტეტი, თბილისი, საქართველო*
*** აკადემიის წევრი, საქართველოს მეცნიერებათა ეროვნული აკადემია; რ. აგლაძის სახ. არაორგანული ქიმიის და ელექტროქიმიის ინსტიტუტი, თბილისი, საქართველო*

მაღალი სიმტკიცისა და დრეკადობის პოლიმერული ბოჭკოები გამოიყენება მაღალი სიმტკიცისა და დარტყმითი სიბლანტის მასალების წარმოებისთვის, რომლებსაც ამავე დროს აქვს დაბალი სიმკვრივე. ერთ-ერთ ასეთ მასალას წარმოადგენს არამიდის ბოჭკოებისგან დამზადებული მაღალი სიმტკიცის კომპოზიტი, რომელიც გამოიყენება ჯავშნების წარმოებაში. ამ მასალების მექანიკური დამუშავება საკმაოდ რთულია. საჭრელი ინსტრუმენტის დაბალმა მედეგობამ შეიძლება გამოიწვიოს მასალის განშრევება, ბოჭკოების გაწყვეტა და ჭრის ზონაში ტემპერატურის მატება, რაც საბოლოო ჯამში თერმულად არღვევს მატრიცას. ამ პრობლემის გადასაჭრელად შეიქმნა პლაზმური რკალური ჭრის ტექნოლოგია, რომელიც თავიდან გვაცილებს მასალის განშრევებას და რღვევას. მასალა მაგრდებოდა წყლით გაცივებულ სპილენძის ორ ფირფიტას შორის და ჭრის ზონაში მიეწოდებოდა წყლის ჭავლი. ეს უზრუნველყოფდა ჭრის ზედაპირის მონოლითურობის შენარჩუნებას და ადვილად დამუშავებას რღვევის გარეშე. კვლევები ჩატარდა როგორც შეკუმშული ჰაერის გარემოში პლაზმური რკალური ჭრისას, ასევე გადახურებული წყლის ორთქლში ჭრის პირობებში.

REFERENCES

1. Ertekin M. (2017) Aramid fibers: fiber technology for fiber-reinforced composites, pp. 153-167. DOI:10.1016/B978-0-08-101871-2.00007-2. https://www.researchgate.net/publication/317336884_Aramid_fibers.
2. Aramid fiber characteristics http://www.aramid.eu/characteristics.html
3. Aramid fiber (Kevlar / Twaron) – Properties and Applications (2015.10.15). http://www.azom.com/article.aspx?ArticleID=1384
4. Sabashvili Z.V., Tavkhelidze D.D., Mchedlishvili Z.T. (2005) Water vapor as a plasma-forming medium. Problems of mechanics. *International Scientific Journal,* 4(21): 79-83. file:///C:/Users/TATA/Desktop/irodonaia,+1.pdf.
5. Sabashvili Z., Loladze T., Kenchiashvili N. (2015) Effect of temperature and water vapor pressure on surface quality of the cutting during water vapor plasma cutting. Book of abstracts. International Conference "Innovative Technologies in Metallurgy and Materials Science", p. 70-71 (16-18 July, 2015). Georgian Technical University. Tbilisi, Georgia. https://gtu.ge/ctmf/pdf/conferences/file1.pdf.

Received March, 2025