New design and technological solutions for creating a composite materials recycling tool and methods of their ultra-jet diagnostics

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Abstract. The article presents the results of two interrelated studies. The first one is related to assessing the possibility of using a water-polymer ultra-jet as a diagnostic tool for cutting devices that are used for plastic recycling. The second one is related to the development of a new tool design. As a result of the research, it is shown that both the method of water-polymer diagnostics and the proposed design of the knife have prospects to practical application. Rapid wear of the tools for recycling polymer materials is the primary problem that is advisable to eliminate in first order because the idle equipment leads to financial losses. Therefore it is necessary to develop tools with high values of wear resistance and which at the same time have a low cost. A model of a prefabricated tool for recycling composites is proposed, which potentially has high performance properties. The main feature of new tool is its geometric configuration that allows to increase the tool resource and significantly saves the material for its manufacturing. The increase of resource occurs due to the following: if the cutting plate of the tool is worn, it can be removed off the tool, flip it 180 degrees and reinstall. Economy of the material is also due to a decrease in size of the plate, which is fixed to the tool body with countersunk screws head. The research results are confirmed by comparative analysis of various diagnostic methods and strength analysis of the tool.

1. Introduction

Ultra-jet diagnostic technology (UJD) was developed in Bauman Moscow State Technical University and has been widely used to assess the quality and resource of functional coatings, residual life of structures, the performance properties of the surface layer, study of abrasive-liquid material resistance, etc. [1-3]. The advantage of UJD is quick access to the necessary information (for determining the quality of the diagnosed material for instance) about the operational and technological parameters characterizing the surface layer state of the material of various technical objects and the ability to create simulated local effects on the material [2]. One of the most attractive benefits of UJD is that it can be used already on finished parts, real final components, so there is no need to manufacture special samples for testing.

The result of the interaction of a high-speed liquid jet with the surface of the diagnosed material is the creation of a hydro-cavern. The hydro-cavern is a pit on the surface of the material made by the action of the UJ on it. UJD is based on the dependence analysis between the local characteristics of the hydro-cavern in diagnosed area of the surface and its quality parameters.
Wide prospects for UJD are opened in case of using suspensions of different composition and structure as a special diagnostic tool. An ordinary suspension is a combination of liquid and something else that does not dissolve in that liquid.

When an ultra-jet reaches a solid target made of some kind of the material, this material produces very small particles. The water that contains that particles is called suspension in our case too. Suspensions can consist of more than two components, depending on the characteristics that are to create: ultra-jet of water, cavitating jet, abrasive-liquid suspension, multiphase suspensions. For instance, suspension with ice crystals can be used as such tool in special machinery industry [2, 3]. It can be used as a tool that simulates the aggressive environment of ice impact. Their use suggests that the object of diagnostics is affected by an impact similar to the actual operating conditions, for example, water-jet effects for pumps that are used for pumping petroleum products, coal, etc. It should be noted that in contrast to some well-known methods, such as evaluating the wear resistance of materials with abrasive-liquid jets, the proposed UJD technology uses ultra-jets with a power flow density of about 0.5 MW/mm², which corresponds to the power density of industrial lasers [4].

2. The problem and proposed solution
Wide technological and diagnostic capabilities of UJD allow us to find new areas of application. Thus, the analysis showed that the existing cutting tool (knives), on the market, for the recycling of polymer materials had a number of drawbacks: low resource, the need for frequent overloading and dismantling of the tool, the complexity of installing and balancing rotors – the main advantage of installations for recycling, etc. [5, 6, 7]. One of the obvious ways to modernize the tool is changing the material from which it is made and in this case, there may be a large number of possible applications not only of various materials, but also coatings, hard-facing methods, etc. At the stage of technology development, that is, at the preliminary stages, it is necessary to have diagnostic methods that will allow fast and reliable access to information about the operational properties of the tool/knife material. Field tests are the most reliable and provide unambiguous information about the tool’s useful operation time and quality, but they take very long time, about 160 hours on average.

Taking into account the experience of using the UJD, an attempt was made to apply a combined ultra-jet, which would include a material – polymer powder – that interacts with the knife. In other words, a suspension consisting of water and polymer powder particles was used. For experiments, polymer powders identical or similar in properties to the processed material were used, that is, the technologically closest and affordable physical and chemical analog [8].

The modification of the ultra-jet can increase the functional and information capabilities of the UJD method. At the same time, the results of ultra-jet interactions, first of all, the nature and geometric parameters of the formed hydro-caverns, products of hydro-erosive destruction, mass-geometric parameters of the object of research contain objective control and diagnostic information about its operational and technological characteristics [9].

3. Ultra-jet flexibility
It should also be noted that the UJD method, among other things, has the ability to vary a number of technological parameters. In particular, it is possible to change the concentration of the powder (that is added to the ultra-jet of liquid), the jet velocity, the speed or vary the distance from the jet-forming focusing tube to the surface of the sample. This, firstly, provides the possibility of expanding the range of changes in the power flow density of the ultra-jet. Secondly, it provides a variation of the energy disequilibrium of physical processes that are similar to the actual operating conditions of this cutting tool. This provision determines the relevance of the research topic and allows us to formulate a goal consisting in a scientific and methodological justification of the possibility of using an ultra-jet as a diagnostic tool.

4. Description of the experiment
A schematic diagram of the UJD using a modified polymer powder ultra-jet is shown in Figure 1.
The Polyamide-12 powder that is usually used in selective laser melting technology in our case was used as a modifier for the ultra-jet of water. So, we managed to achieve a water-polymer ultra-jet just by adding polymer powder into the ultra-jet of water.

The UJD experiment using a modified ultra-jet (water-polymer ultra-jet) was performed using a water-jet cutting machine made by Flow System (USA) – “Flow Mach 3” model. The pressure in the system was $P=400 \text{ MPa}$, the distance from the cross section of the focusing tube to the surface of the knife was $h=4 \text{ mm}$, the feed rate of the nozzle head was $S=0.41 \text{ mm/s}$, the concentration of polymer powder was $C=0.2 \text{ kg/min}$ (table 1).

| Parameter  | Value  |
|------------|--------|
| $P$ (MPa)  | 400    |
| $h$ (mm)   | 4      |
| $S$ (mm/s) | 0.41   |
| $C$ (kg/min) | 0.2   |

As samples for the research and testing of the UJD method, we selected knives for the PM250 rotary crusher model, manufactured of bimetal (Steel 3 (base) – Steel 9KHF) [10]. A total of four knives were considered with the following modes of heat treatment in accordance with table 2.

It should be noted that the use of bimetal blanks for the manufacture of knives is a novelty and has been tested for the first time.
Table 2. Information about the knives and their modes of heat treatment

| Marking | Mode of heat treatment |
|---------|------------------------|
| №1 (Z + V) | quenching 840°C, cooling in a flow of water |
| №2 (Z + V + O) | quenching 840°C, cooling in water flow, tempering 160°C, 2 hours |
| №3 (Z + M) | quenching 880°C, cooling in oil |
| №4 (Z + M + O) | quenching 880°C, cooling in oil, tempering 160°C, 2 hours |

5. Results
For a comparative analysis of the results of UJD, the knives were tested using traditional methods: friction tests, full-scale tests and micro-hardness measurement [12, 13].

Four sets of bimetallic knives made from 9KHF – Steel 30 with marking №1-4 were transferred to the limited liability company “Astrelati” for industrial (full-scale) tests. The knives were installed in a rotary crusher model PM250 together with standard knives made of steel 6KHV2S [14]. Figure 2 presents the photos of PM250 and installed knives. The working time of the cutting tool was 160 hours [15, 16]. The recycled (shredded) material was defective polypropylene structures.

Figure 2. (a) Rotary crusher, (b) PM250 modules and a cutting tool fixed in the rotor of the crusher.

After the experiment and dismantling of the tool, the following parameters were measured: changing (increasing) the radius of rounding and the number of chips on the cutting edge of the knife, changing the front rake angle etc. [17, 18]. The obtained data were compared with the value of the depth of the hydro-cavern after UJD [19], which was determined using the profilometer-profilograph BV-7669 (produced by the research institute “Measurements”, Russian Federation). The example of obtained data by this equipment is presented in figure 3. It depicts the contour of the hydro-cavern and its depth (the profile of the surface).

Figure 3. Example of data produced by BV-7669.

The friction tests were carried out using a classic friction test rig (figure 4). The contact load was 0.2 kg and was determined by the weight of the rod [9]. Micro-hardness was measured using a
Micromet-II micro-hardness tester with a load of 500 g. according to GOST 9450-76 (Measurement Of Microhardness by Pressing Diamond Tips) [11].

Legend:
1 – electric motor
2 – foundation slab
3 – engine control unit
4 – linear drive with flywheel
5 – load cell
6 – linear bearing
7 – cylindrical shaft of linear guide
8 – rotating table with sample
9 – experimental sample (knife)

Figure 4. The device for friction testing.

Based on the results of measurements, the values of the pairwise correlation of each of the informative parameters were calculated (table 3).

|    | a         | b         | c         | d         | e         | f         | g         |
|----|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| a  | -         | 0.93      | 0.88      | 0.87      | 0.91      | 0.97      | -0.74     |
| b  | 0.93      | -         | 0.91      | 0.94      | 0.92      | 0.81      | -0.79     |
| c  | 0.88      | 0.91      | -         | 0.99      | 0.99      | 0.81      | -0.95     |
| d  | 0.87      | 0.94      | 0.99      | -         | 0.99      | 0.77      | -0.95     |
| e  | 0.91      | 0.92      | 0.99      | 0.99      | -         | 0.85      | -0.95     |
| f  | 0.97      | 0.81      | 0.81      | 0.77      | 0.85      | -         | -0.68     |
| g  | -0.74     | -0.79     | -0.95     | -0.95     | -0.95     | -0.68     | -         |

a Rounded cutting edge radius (mm).
b Changing the front rake angle (degrees).
c The number of chips per unit length of the cutting edge.
d The ratio of the cutting edge's ablation area to the length (mm).
e Hydro-cavern depth (mm).
f Depth of the friction test cavity (μm).
g Micro-hardness (MPa).

6. The idea of a new tool
In this regard, it was suggested to analyze other possible ways to improve the tool that combines a combination of materials, in particular, the use of a tool with a removable working plate (figure 5). As a result, the design of the knife was proposed, which uses a replaceable double-sided plate made of high-speed steel P6M5, which has shown itself well as a result of water-polymer UJD (figure 6). A
replacement plate with a diamond-shaped cross-section that allows, firstly, to make its turn to change the cutting edge, and secondly, to redistribute the loads acting on the working edge perpendicular to the plane in the scheme, from the mounting screws to the knife body.

Figure 5. Traditional and promising tool for recycling PCM:
(a) – Traditional knife, (b) – Bimetallic knife, (c) – Knife with replaceable plates.

The potential increase in the performance of the assembly tool is as follows:

- The use of high-wear-resistant alloy replacement plates as a material reduces the time associated with knife service (reloading, rotor balancing, installation and adjustment of the gap between the knives), reduces the amount of metal impurities in the processing of composite materials components, which increases the cost of raw materials
- Reduce the time to change knives by allowing the cutting plate to be rotated 180 degrees after using one side. At the same time, these types of work can be carried out without removing the tool from the rotor, which avoids balancing and setting a gap between the knives.

The plate is attached to the knife body using titanium screws with a countersunk head (figure 5 b). In contrast to the traditional design of ordinary and bimetal knives (figure 5 a, b), the new knife saves material by reducing the size of the plate and the consumption of tool material.

The proposed design was calculated for strength in the SolidWorks program by simulating the load on the product. The calculation results are shown in figure 7. According to the scheme (figure 5 c), a sample of the knife was made for the purpose of conducting full-scale tests (figure 8).

7. Discussion
Table 3 shows that the depth of the hydro-cavern corresponds to the results of other tests and the method may be equally valid for practical application.

The ideas for improving the recycling tool are based on the use of combination of several materials and the use of exchangeable working plate; however, further consideration revealed the disadvantages
of bimetallic knives, due to the fact that, like an all-alloy knife, the bimetallic one also needs to be removed from the rotor for recasting, which requires a lot of time and subsequent balancing of the crusher rotor [20]. In addition, a significant amount of tool material is simply not used in this design, so, that’s why the new design of the cutting tool was proposed. The use of an additional diamond-shaped section of the plate increases the reliability of fastening and reduces the number and cross-section of fixing screws, which has a positive effect on the cyclic strength of this product.

8. Conclusion
Based on the data obtained (table 3), it can be argued that the UJD method is highly informative, not inferior to the traditional method of friction tests. In addition, which is especially important in practice, there is a high correlation between the results of field tests and informative signs of UJD.

Furthermore, in comparison with the method of friction testing, water-polymer UJD has a number of advantages, such as: the rapid diagnostic process; the formation of a powerful wave perturbation in the zone of influence of water-polymer ultra-jet; simulating the working conditions of the tool for a long time of operation; the creation of shock variable loads when polymer particles collide with the surface of the knife. Additionally, a promising design of the knife with the ability to reverse the plate has been developed, which has significant advantages that will soon be tested during field tests. Most important features of this knife include reduction of service time for it and increased cost of produced materials.
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