Analysis and synthesis of ecological installations for recycling waste polyurethane foams

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Abstract. Recycling and utilization of polymer materials is one of the most urgent tasks for modern science and technology. The polymeric materials polyurethanes (PUs) play a big role in different applications. The morphological approach is used as a way of designing, thinking, finding solutions and variants for the polyurethanes recycling technology. This method use as a part of the design process, especially in the conceptual design stage. This approach allows to search for innovative engineering solutions and choose the rational variants and compare them. This paper presents and discusses an morphological approach for solving the polyurethanes recycling problems.

1. Introduction
Modern scientific and technological progress is associated with the global use of natural resources and the accumulation of man-made waste in particular plastics. The production of plastics and exactly polyurethane is growing rapidly (figure 1) [1,2].

![Figure 1. Worldwide polyurethane production.](image)

Flexible polyurethane foam (FPF) hold a significant amount of space in the polyurethane industry. It is used in a very wide range of applications, especially in mattresses, upholstered furniture and in vehicles. As an example, nearly 90% of mattresses produced in the EU contain polyurethane foam and over 90% of furniture upholstery is made of polyurethane foam. The EU’s production of flexible
Polyurethane foam is of around 900,000 tonnes [3]. In industrialized countries, solid household waste is generated in significant quantities, and its annual growth is from 3% to 10%. At the same time, it is estimated that no more than 10 thousand tons are processed, and the rest of the huge part in the form of garbage is taken to landfills.

The FPF waste can be classified as follows:

- waste of injection-molded thermosetting polyurethanes (sprues, flakes, chips in the form of tape from turning shafts, etc.);
- waste of soft and hard polyurethane foams (figure 2).

The polyurethane waste is prohibited to be exported to landfills, incinerated (when incinerated, cyanide (XCN) is formed, etc. Only in the production of PU the share of waste is up to 3-5%.

![Figure 2. Flexible polyurethane foam waste, crushed to 5-10 mm.](image)

2. Flexible polyurethane foam utilization

The following FPF recycling processes are best known [4-9]:

- thermal decomposition by combustion;
- mechanical grinding followed by the use of the resulting crumbs as a filler in various composite materials;
- depolymerization with the formation of low molecular weight products.

Existing grinding technologies allow you to grind polyurethane foams to pieces with a minimum size of 5 mm. The problem of fine grinding of FPF with a particle size up to 200-500 micrometers has not yet been solved. The problem lies in the physical and chemical properties of materials – their low density (10-120 kg/m³) does not allow for fine grinding using knife mills. If the rotation speed of the knives increases, the particles begin to melt with the release of toxic substances. FPF is possible to grind at cryogenic temperatures, but these technologies are not economically justified.

The disadvantages of the known technical solutions are:

- low efficiency of grinding materials;
- low heat exchange, sometimes resulting in melting of the material being crushed;
- inefficient heat removal from the processed material;
- lack of intensive mixing;
- high resistance to movement of the machining tool;
- insufficient heat transfer;
- low environmental friendliness.
3. Advanced morphological approach for FPF utilization

The Advanced Morphological Analysis (AMA) is based on cluster analysis, set theory, set of rules and modeling [10,11].

The advanced morphological approach are used for the following purposes:
- Problem definition and formulation;
- To generate a better understanding of problems or systems;
- Investigations of existing or developing systems.

At the first stage a morphological matrix was created (table 1) (figure 3). The morphological matrix contains the reference known technical solutions (figure 4,5) and the selected solution (figure 6).

### Table 1. The morphological matrix of the main physical principles of FPF grinding.

| Attributes          | Option 1 | Option 2 | Option 3 | Option 4 |
|---------------------|----------|----------|----------|----------|
| Working substance   | Air      | Sand     | Water    | Inert gas|
| Type of grinding    | Splitting action | Crushing action | Abrasive-crushing action | Cutting action |
| Temperature regime  | Elevated temperatures. | Ambient temperature | Reduced temperatures | Cryogenic temperature. |
| Location            | Vertical | Horizontal | Inclined | Rotating |

![Figure 3. The morphological matrix with the principles of grinding.](image)

![Figure 4. High-speed abrasion at low temperature.](image)

![Figure 5. Wet grinding in rotating mills.](image)

![Figure 6. The synthesized engineering solution.](image)
An experimental grinding plant has been developed and tested. Its design is based on structural synthesis methods. The technological process takes place in a gas-air mixture, while cavitation occurs in some modes. During the experiments, it was possible to achieve a stable grinding process, as well as to obtain a narrow fraction of the crushed material. Experiments have shown that fine polyurethane waste can be added to the initial mixture in an amount of up to 10% (polyol) in the production of foam rubber and obtain samples with a uniform structure (figure 7) [12].

Figure 7. Experimental samples of polyurethane foams containing from 5 to 10% of the crushed material.

Technological processes for processing and reuse of FPF include (figure 8):
- Coarse grinding of waste to a particle size of no more than 20 mm.
- Reduction of FPF to a particle size of no more than 500 micrometers in a water-air mixture using cavitation technologies.
- Introduction of crushed waste into the polyol component.
- Production of molded or block polyurethane foam with a particle content of up to 10 percent.

Figure 8. The technology of FPF processing.
4. Conclusions
The morphological approach let:
- Achieve a better understanding of the problem and technology development;
- To generate and analyzed set of morphological variants;
- Synthesize the physical principles of recycling technology;
- Realize compare different technologies for utilization;
- Technology demonstrator created.

The proposed technology makes it possible to efficiently process FPF waste by fine grinding. The experiments made it possible to conclude that it is permissible to introduce crushed FPF waste into products, while:
- The content of crushed waste should not exceed 10%;
- The particle size of crushed polyurethane waste should not exceed 500 micrometers.

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