Surface modification by deformational cutting for improving the bonding strength of polymers and polymer composite materials with metals and with each other

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Abstract. This article covers the analysis of possibilities for the use of deformational cutting method as a tool for the creation of macroreliefs designed for increasing the strength of connections between materials which are characterized by a low adhesive quality. Surface reinforcement of carbon-fiber materials with sheet metal is also considered in this work. The results shown prove a major increase in strength values. All samples with macrorelief obtained by deformational cutting show high strength in exfoliation and shock tests with a changing damage mechanism from adhesion to cohesion.

1. Introduction

Metal alloys, polymeric and composite materials are widely used in industry. Each group has its significant advantages before other groups in terms of price, strength, hardness, wear resistance or other parameters. It would be reasonable to combine advantages of different types of structural materials in one prefabricated part structure while each component of an assembly unit is responsible for its own functionality. Assembly method is key factor in functionality, reliability and manufacturability of the prefabricated unit. Adhesive joints are able to connect various materials that differ from each other both in properties and thickness, and not to weaken the parts subject to connection. Sometimes bonding is the only possible way to connect the unit parts. The disadvantages of adhesive joints include low tear resistance, instability of physical and mechanical properties as well as the need for special treatment of the surface before bonding [1].

Modern engineering also sees a widespread use of laminated metal-polymer composites or metal-filled plastics - materials consisting of alternating thin sheets of metal alloys and polymer layers or polymer composite materials: organic, carbon, or fiberglass plastics (PCM). Such hybrid materials are distinguished by high strength and fracture toughness values achieved due to the fact that properties of their constituent components complement each other. Metal-polymer composites are important for applications, e.g. in aircraft structural elements, which makes it possible to reduce their weight and significantly improve the structural life [2-3]. Sports equipment (snowboards, skis) also has in its structure compounds of metal – carbon composite – antifrictional sliding polymer layer [4]. Reduction in the weight by 80 kg of new car models was achieved specifically due to a combination of adhesive joints of PCM and metals [5]. Not only adhesive joints are used for bonding of metals with polymer or polymer composite materials (PCM) or combinations thereof, but also joints obtained directly during the polymerization process of the polymer and/or PCM binder [6-8].
Modern adhesives and binders have good adhesion to PCM with a thermosetting matrix (glass-, carbon-, organic plastics, but the strength of their adhesive bonding to metals and thermoplastic polymers is insufficient [9-10]. If bonding or polymerization is made for connection, preliminary treatment of the surfaces by various methods is of particular importance. It plays a crucial role in ensuring durability of connections during operation. The objective of preliminary surface treatment is to create conditions for a physical and chemical interaction of surfaces to be bonded [11].

Currently, surfaces to be bonded are exposed to the procedures of degreasing, pickling, oxidation, phosphating, zinc plating, surface activation by electrical discharge, ultraviolet irradiation, flame treatment, etc. to ensure strength of joints "metal-PCM", "metal-polymer" and "polymer-PCM" [12]. More reliable compounds allow one to make the fixing microelements on metal via punching combs, pin milling or pressing, welding, and so forth (Figure 1) [13-15]. The topical issue is miniaturization of fasteners and ensuring the reproducibility of the required quality of their installation, which is quite a difficult technological challenge [9].

![Fixing elements for connection of metal with PCM](image)

**Figure 1.** Fixing elements for connection of metal with PCM [6, 13].

2. **Deformational cutting for surface macrostructuring.**

An existing increase in strength and reliability of both glue conjunction and compound obtained via polymerization of the binder can be enriched via regular small pitch relief with a high height to pitch ratio. The creation of the deep micro or macroreliefs via deformational cutting (DC) is the most promising method.

The DC method is based on simultaneous cutting of the surface layers and their plastic deformation [16]. The cut layer is not removed completely from the blank, being mechanically connected with it from its narrow side. A set of the cut surface layers that retains the continuity of its connection with a blank forms a enhanced macrorelief in the form of finning or pin fins on the treated surface (Figure 2). DC technology boasts high performance and a wide range of sizes of the relief obtained and can be implemented both on specialized and unified metal-cutting equipment [17]. Turning machines are used for the processing of cylindrical surfaces and sheet bars using the mandrels. Planing and milling machines are used to process planes. DC technology allows obtaining a macrorelief only on ductile materials such as copper, aluminium and their alloys, titanium, steels, thermoplastic polymers, etc. Parameter which characterizes the plasticity of the material to the maximum extent is the relative elongation value δ₁₀. For the materials with δ₁₀ <18% the cut layer does not remain in the fin form on the workpiece, but is separated in the form of chips [17].
The typical profile of macrorelief in the form of finning which is obtained through DC technology and its geometric parameters are shown on Figure 3. For vertical fins, there is the following relationship between the parameters of the fins and technological processing parameters [17]. When turning is made, fin spacing $S$ is determined by the tool feed based on one part revolution: $S=S_0$, for milling operations - feed per tooth: $S=S_{\text{tooth}}$, when shaping - feed per double stroke: $S=S_{\text{fds}}$.

The width of the interfin gap ($b$) is determined by the fin spacing ($S$) and undercutting angle ($\phi$) according to the function as follows:

$$b = S \cdot (1 - \sin \phi)$$  \hfill (1)

where $\phi$ is the angle of undercutting.

Fin top angle is equal to the undercutting angle $\phi$.

Let us consider an option of exposure of an adhesive joint to a uniform separation in an interfin gap. The strength of adhesive joint is caused both by the adhesion interaction of surfaces to be glued with an adhesive layer, and the cohesive strength of the adhesive itself. The ratio of the interfin gap width...
and height (fin height) is an important factor that enables maximum strength of the adhesive joint with the surface treatment using DC technology. The use of shallow grooves will not provide a reliable adhesive bond between the adhesive joint and cladding metal. The fins of excessive height will result in an increase in steel intensity of the cladding layer, while the production technology will become more difficult.

A reasonable option is an adhesive joint which functions with fully implemented values of adhesive permissible tensile strength $\sigma_a$ (cohesive strength), i.e. when the failure occurs on the line A-B (Figure 3b) without detachment from the lateral sides of the interfin gap. Figure 3b shows with small arrows the tangents $\tau_a$ and normal lines $\sigma_a$ of adhesion bond stress at the interface adhesive-metal. Inclined places of the interfin gap (triangular fin pointing and bottom of the interfin cavity) are exposed both to normal $\sigma_a$ and $\tau_a$ tangential stress lines. Vertical walls are exposed to tangential stresses only. Let us take as an assumption a uniform distribution between normal and tangential stresses along the perimeter of interfin cavity. Such approach is justifiable for an estimate calculation [18], and is used for adhesive joints of small length [6], which is typical for interfin gap areas.

The condition of full implementation of adhesive cohesive strength means that the total shear and tensile strength of adhesive bonds along the perimeter of the interfin gap should be higher than the adhesive tensile strength along the line A-B. This position allows to minimize the macrorelief height while ensuring the maximum strength of the adhesive joint.

Let us consider the layout of adhesive interaction between the adhesive and metal along the perimeter of interfin gap on the area of the adhesive joint with a length equal to fin spacing. (Figure 3b). The force required for cohesive failure of adhesive over the area with the length equal to the fin spacing will amount to: $P=\left[\sigma_a\right]\cdot S$, where $\left[\sigma_a\right]$ is a permissible uniform tensile strength of the adhesive.

The total component of shear and normal stresses of adhesive bonds in the direction of tensile force with regard to the length of their impact on individual areas should be recorded as follows:

$$P=\frac{\left[\tau_a\right]\cdot S\cdot \sin \varphi}{\sin \varphi}\cdot \cos \varphi + \frac{\left[\sigma_a\right]\cdot S\cdot \sin \varphi}{\sin \varphi}\cdot \sin \varphi + \left[\tau_a\right]\cdot \left(h - \frac{S\cdot \sin \varphi}{tg \varphi} - \frac{S\cdot \sin \varphi}{tg \varphi}\right) + \frac{\left[\tau_a\right]\cdot (S - S\cdot \sin \varphi)}{\cos \varphi}\cdot \sin \varphi + \frac{\left[\sigma_a\right]\cdot (S - S\cdot \sin \varphi)}{\cos \varphi}\cdot \cos \varphi + \left[\tau_a\right]\cdot h. \tag{2}$$

where $\left\{-\left[\tau_a\right]\right\}$ is a shear strength of the adhesive bond of the adhesive and material to be glued,

$\left[\sigma_a\right]$ is the ultimate uniform tensile strength of the adhesive bond between the adhesive and material to be glued, h - fin height.

If we equate tensile strength of the adhesive over the area with the length equal to the fin spacing, with the sum of adhesive interaction components along the perimeter of interfin gap, we will receive the following after simplification:

$$\left[\sigma_a\right]\cdot S = \left[\sigma_a\right]\cdot S\cdot \sin \varphi + \left[\sigma_a\right]\cdot S\cdot (1 - \sin \varphi) + 2\left[\tau_a\right]\cdot h. \tag{3}$$

Based on this expression it is possible to obtain a minimum height of interfin gap for this finning spacing which ensures the absence of adhesion failure along its perimeter (i.e. ensuring maximum strength of adhesive joint based on its ultimate uniform tensile strength:

$$h \geq \frac{S\cdot \left\{|\sigma_a| - |\sigma_a|\right\}}{2\left[\tau_a\right]} \tag{4}$$

As it can be seen from the expression, the macrorelief is required in the first place for adhesives with a significant difference between the cohesive and adhesive strength values. The greater the difference in these values, the deeper the interfin gap must be for this combination adhesive-metal.
The second important conclusion that can be drawn when analysing this formula, is the absence of undercutting angle therein which determines the ratio of the width of the interfin gap to its spacing: \( b/S = 1 - \sin \phi \), i.e. the strength of the adhesive joint is not affected by the interfin gap width (for this spacing and fin height).

3. Preparation of the surfaces for glueing by using the DC technology

Materials with a low adhesion were selected to assess the efficiency of use of macroreliefs obtained through deformational cutting in order to enhance the strength of adhesive joint: austenitic heat-resistant steel 316L, Teflon and ultrahigh molecular weight polyethylene (UHMW-PE).

Table 1 shows the parameters of samples with the macrorelief obtained via DC technology. Relief cross-sections are shown for samples No. 1-4 in the Table 1, top view of the structure is shown for the sample No. 5 on Figure 4a.

Macrorelief No. 1 on the steel samples was made on the strip with an initial thickness of 0.76 mm. Macrorelief (sample No. 2) was performed on one side of the Teflon cube having a side of 11 mm. Macrorelief on samples 3-6 was performed on a tape made of UHMW-PE with a width of 10 mm and a thickness of 0.8 mm. The tape was obtained through the planing of the end face of the sheet with the thickness 10 mm via free cutting method. When receiving the reliefs on the polymers, the peculiarities of their processing via DC method described in [19] were taken into account.

The macrorelief had inclination on all samples to increase strength of the adhesive joint. When putting samples No. 1 to the delamination test and during uniform tensile test of samples No. 2, no tearing of the adhesive from the interfin gap was recorded. The failure occurred along the adhesive.

For samples made of UHMW-PE No. 3, even the use of inclined fin with large inclination angle of the fins of 32° during a delamination test was accompanied by the absence of cohesive failure. Epoxy adhesive "slipped out" even from the inclined interfin gap. The Figure 4b shows an area with epoxy glue following delamination of UHMW-PE, which remained on the carbon fibre and is a replica of the interfin gaps shape of the sample No. 3. This fact required the search for other macrorelief configurations on UHMW-PE which were implemented on samples No. 4 and 5. Interfin gap on the sample No. 4 has an expansion at the bottom part by forming a locked cavity for a cured adhesive. The width of the interfin gap is 130 µm in the expanded part and 60 µm in the narrow part. The principle of obtaining such subsurface cavities via DC technology is described in [20].

Macrorelief on the sample No. 5 was obtained through double finning of the tape made of UHMW-PE with the finning pitch on each pass of 0.3 mm and with the pass crossing angle 13°. After the processing the pin-type surface of the tape represented in its essence a variety of inclined "villi" with a length of 1.3 mm. The pin has in its cross section a rhombus shape with a side of 0.15 mm. The inclination of pins was 70° from the vertical. 1000 pins were arranged on every square centimeter. The principle of obtaining the pin structures is described in [21].

| Sample No. | 1 | 2 | 3 | 4 | 5 |
|------------|---|---|---|---|---|
| Material to be glued | Steel 316L | Teflon | UHMW-PE | UHMW-PE | UHMW-PE |
| Type of structure | ![](image1) | ![](image2) | ![](image3) | ![](image4) | ![](image5) |
| Pitch, mm | 0.4 | 0.5 | 0.4 | 0.3 | 0.3 |
| Height of relief, mm | 0.67 | 1.0 | 0.55 | 0.4 | 0.3 |
| Interfin gap, mm | 0.16 | 0.15 | 0.15 | 0.13/0.06 | – |
| Fin, or pin fin inclination, deg | 8 | 15 | 32 | 0 | 70 |

Table 1. Parameters of the macrorelief of samples to be glued and test conditions.
### Table 2

| Material of counterpart | Adhesive trade mark | Teflon | Carbon-fiber | Carbon-fiber | Carbon-fiber |
|-------------------------|---------------------|--------|--------------|--------------|--------------|
| Carbon-fiber            | Toolfusion 1A/1B (Airtech) | Russian epoxy binder. Specification 07510508.90-94 | Araldite 2011 (Huntsman Corporation) | Araldite 2011 (Huntsman Corporation) | Araldite 2011 (Huntsman Corporation) |

#### Figure 4.
Micropin-type surface of UHMW-PE for bonding (a) and carbon fibre PCM view following delamination of finned tape UHMW-PE (b).

#### 4. Test results
During the test of sample No. 1 (6 tests) using impact machine Walter+Bai AG PH150 with impact energy of 50 J, fracture energy \( A_n = 11.5 \text{ J} \) was recorded, which resulted in the value of specific impact toughness \( A_n = 228 \text{ kJ/m}^2 \). Samples with a cladding metallic layer without macrorelief exfoliated completely from carboplastic (Figure 5b), whereas the samples with microrelief exfoliated exclusively by the carboplastic layers (Figure 5c). Table 2 show that 53-60% increment in the value of specific impact strength of sample No. 1 is attained when compared with sheets without macrorelief [9].

#### Figure 5.
(a) Test scheme on impact-testing machine and samples after tests (b) without macrorelief on metal, (c) with macrorelief obtained via DC.
Table 2. Destruction energy of samples in tests on impact-testing machine [9].

| Sample number | Cladding without relief | Without cladding |
|---------------|-------------------------|-----------------|
| Destruction energy An (J) | 11.5 | 7.2 | 4.1 |

Six tests were also carried out for the sample No. 1 to measure the peeling strength under the angle 90°. Test configuration is given on Figure 6a. The tests were conducted on a universal testing machine INSTRON 600-DX. The size of the contact conjunction area metal - carbon fibre was 25 x 100 mm. The samples were stretched at the speed of 25 mm/min, and an average breaking force was measured during the test. On the next phase, the force was converted into the line force, measured in Newton per 1 mm sample width (or in kN/m).

A multiple increase in the delamination force of the sheet metal having a macrorelief compared to cladding with smooth metal plates was recorded. Plates with no macrorelief flaked simultaneously over the entire bonding area (at force orders of magnitude). Cohesive failure occurred for finned samples, no tearing of the epoxy binder from macrorelief was observed (Figure 6). An average linear breaking force was within the range 4.4-9.1 kN/m [9].

![Figure 6](image)

**Figure 6.** (a) scheme of 90° exfoliation tests. External view of samples after 90° exfoliation tests: (b) plated slab with macrorelief; (c) cross section of a plated layer with macrorelief after exfoliation.

The strength of adhesive joint is performing a uniform tensile of the samples No. 2 was measured when gluing the couple Teflon - Teflon. Teflon blocks were glued with sides having an applied macrorelief. Breakout force was recorded with the use of dynamometer model 9257 V made by "Kistler". When using EDP epoxy adhesive, a couple of glued samples withstood the greatest load: they had mutually perpendicular directions of microfins on the cube sides. The maximum tensile strength was 12 MPa. When bonding Teflon+Teflon by using hot-melt glue (ethylene vinyl acetate), tensile strength amounted to 5 MPa.
Strips made of UHMW-PE bonded with an epoxy adhesive Araldite 2011 were tested for delamination at an angle 90° from carbon fibre. Microfinning direction was along the strip being delaminated. The test results are shown in Table 3.

| Sample number | Coarse-grained abrasive paper | Without surface treatment |
|---------------|-------------------------------|---------------------------|
| 3             | 1.2                           | 1.0                       |
| 4             | 1.7                           | 0.15                      |
| 5             | 4.5                           |                           |

Table 3. Force "per unit of length" of 90° exfoliation of UHMW-PE from carbon-fiber.

5. Discussion

When bonding metal with carbon fiber microfinning on the metal allowed improving the strength of the adhesive joint up to the carbon fibre matrix level. When testing Teflon for uniform separation, the maximum strength of adhesive joint amounted to 12 MPa, which is only two times lower than the tensile strength of Teflon (23 MPa). When testing for delamination of UHMW-PE from carboxplastic, the relief in the form of microfinning did not produce significant results compared to the treatment by means of coarse-grained sand paper. Inclined fins did not provide a locked connection and an adhesive delamination occurred. Interfin gap with an expansion at the bottom part secured an anchor (lock-type) effect. Epoxy adhesive remained in the expansion of interfin gap, its failure occurred in the narrowest part having the width of 70 µm, which resulted in an increase in strength. However, for the sample No. 4, the total area of adhesive bridges subject to tension is five times less than the area of surface to be bonded, which did not allow to fully implementing the strength of epoxy adhesive. When testing UHMW-PE for delamination, bonding surface in the form of inclined micropins turned out to be the most effective in terms of strength. The peel strength value exceeded five times the similar strength for the surface treated by means of coarse-grained sandpaper.

Undoubtedly, the presented versions of macrorelief shapes and sizes are not optimal; however, the first results of strength tests prove the prospects of using the DC technology to enhance the strength of adhesive joints between materials with low adhesive properties.

6. Conclusions

1. Surface preparation of low-adhesive materials using DC method revealed to change from adhesion to cohesion destruction mode.

2. For all samples with macrorelief via DC, there was either interlayer destruction by carbon fabric layers or destruction of epoxy binder on the top of the fins.

3. With double-sided finning of metal sheets DC technology can also be used for the creation of multilayered composite materials based on thin metal sheets and adhesive prepregs – MPCM.

4. Micrelief obtained via deformational cutting exhibited metal–PCM contact strength in exfoliation to the carbon-fiber matrix strength.

5. In the shock tests for samples with microrelief on metal, there was detected an increase in the destruction energy to 60% in comparison with macrorelief free samples on metal.

6. For UHMW-PE only the micropinned surface showed sufficient result.

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References

[1] Adams R et al 1997 Structural Adhesive Joints in Engineering (London: Chapman & Hall) p 360
[2] Vlot A and Gunnink J 2011 Fibre Metal Laminates (New York: Springer Science & Business Media) p 532
[3] Kraemer B 2014 Kleben im Leichbau. Von der Materialherstellung bis zur Reparatur Adhäsion Kleben und Dichten 58(10) 28-31
[4] Galetz M et al 2007 Carbon nanofibre reinforced ultrahigh molecular weight polyethylene for tribological applications J. of Appl. Polymer Sc. 104 4173-81
[5] Lutz A and Schmaltloch S 2014 Composites strukturell kleben Adhäsion Kleben und Dichten 58(9) 32-6
[6] Messler R 2004 Joining of Materials and Structures from Pragmatic Process to Enabling Technology (Burlington: Elsevier) p 816
[7] Troughton M 2008 Handbook of Plastics Joining: A Practical Guide (New York: William Adrey) p 600
[8] Dillard D 2010 Advances in Structural Adhesive Bonding (Burlington: Elsevier science technology) p 656
[9] Zubkov N et al 2016 Surface reinforcement of carbon composites with microstructural metal materials Polymer Sc. Series D 9(1) 91-5
[10] Vermeeren C 2003 An Historic Overview of the Development of Fibre Metal Laminates Appl. Compos. Mat. 10 189-205
[11] Marcus S et al 2006 Fehlervermeidung durch Inline-Monitoring des Oberflaechezustandes Adhaesion Kleben und Dichten 4 20–7
[12] Brockmann W et al 2008 Adhesive Bonding: Adhesives, Applications and Processes (Hoboken: John Wiley & Sons) p 432
[13] Cherevashchenko A 2013 Structural technological solutions for metal–composite compounds operating under peeling stress Probl. Proekt. Proizvod. Konstr.Letatel’nykh Appar. 1(73) 14-20
[14] Komarov G 2016 Trends in Joining Technology of Parts Made of Plastics and Joints with Them Polymer Mat. 10 42-8
[15] Kunststoff 2015 Oberflächen passgenau modifizieren Adhäsion Kleben und Dichten 59(12) 6
[16] Solovyueva L et al 2012 Novel Electrical Joints Using Deformation Machining Technology Computer Modeling IEEE Transac. on Comp., Pack. and Manufact. Techn 2(10) 1711-7
[17] Zubkov N 2001 Features of realization of the method of deforming cutting Tekhnol. Mashinostr. 1 19-26
[18] Chawla K 2012 Composite Materials Science and Engineering (New York: Springer-Verlag) p 542
[19] Zubkov N and Sleptsov A 2010 Production of slotted polymer filter tubes by deformational cutting Russ. Engin. Res. 30(12) 1231-3
[20] Popov I et al 2013 Heat transfer during the boiling of liquid on microstructured surfaces: Part 1: Heat transfer during the boiling of water Thermal Eng. 60(3) 157–65
[21] Zubkov N et al 2014 Using the pin structures of a new type for cooling of electronic equipment Vestn. Mosk. Gos. Tekh. Univ. im. N. E. Baumana, Ser. Mashinostr. 2(95) 70-9