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Effect of Nickel Coating on Bending Properties of SL Polymer

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ABSTRACT

The effect of nickel coating on the bending properties of Stereolithography (SL) parts was investigated. It was found that a thin layer of nickel coating significantly improves the flexural strength and modulus of the SL specimens. The strengthening effect of the coating is dependent on the ratio of the Young's moduli of the coating and the substrate materials, as well as the thickness of the coating.

Keywords: polymers (A), coating (C), mechanical properties (E), prototyping

1. INTRODUCTION

Rapid prototyping (RP) technologies emerged from late 1980's made it possible to fabricate three-dimensional objects directly from a computer model rapidly and inexpensively. The parts produced by these RP processes are made predominantly of polymers, and have been widely used as prototype models for form and fit. In recent years, the RP parts have found increased uses in rapid tooling (RT) applications, such as injection moulds and sand casting patterns. In such applications, the mechanical strengths and rigidity of the polymeric parts are often insufficient and further improvements in these properties are required. Coating RP parts with metals was shown to be a promising route for the fabrication of injection moulds [1]. Although metallization of polymers have been in commercial use for several decades [2,3], most of the metal coatings on polymer materials were for decorative purposes or for shielding of electromagnetic fields in applications such as electronic device enclosures [4]. Mechanical properties of the coated parts were not of major concerns for these applications. To date, little information is available on the mechanical properties of the metal-coated polymer materials, in particularly for the substrates made of photo-cured epoxy resins. To obtain a good understanding on the strengthening effect of the metallic coating on the photo-cured SL resins, the current study investigated the flexural properties of Stereolithography (SL) samples with and without nickel coating using three point bending tests.

2. EXPERIMENTAL PROCEDURES

Test specimens with nominal dimensions of 152.40 mm in length, 19.05 mm in width, and 6.35 mm in thickness were fabricated using Stereolithography Apparatus SL5000 made by 3D Systems Corporation. A set of specimens were built with the 152.40 mm x 19.05 mm side facing up during building (referred to as horizontal orientation hereafter), and another set of specimens were built with the 152.40 mm x 6.35 mm side facing up (referred to as vertical orientation). The specimens were coated with a thin nickel of layer by electroplating, with the thickness varying from 0.08 mm to 0.15 mm. Flexural properties of the coated and non-coated SL polymer were determined using three-point bending test according to ASTM Standard D790-00. Figure 1 illustrates schematically the shape of the test specimens and the experimental setup. The support span L was 101.60 mm. The bending test was conducted using an Instron machine at a strain rate of 0.01/min to a maximum strain of 5%. The flexural modulus E and flexural stress σ were calculated according to the following equations [5]:

$$E = L^3 m / 4bd^3 \quad (1)$$

$$\sigma = 3PL / 2bd^2 \quad (2)$$

Where E is the flexural modulus, σ the flexure stress in the outer fibers at midpoint, L the support span, b the width of the specimen, d the thickness of the specimen, m the slope of the tangent to the initial straight-line portion of the load-deflection curve, and P the bending load. Normally equations (1) and (2) are applicable only to homogeneous materials. In this study, the equations are also used to calculate the *apparent* flexural

stress and modulus for the nickel-coated specimens for direct comparison with the Stereolithography (SL) specimens without coating. The true flexural stresses for the nickel-coated specimens are different from the apparent flexural stresses and are discussed in a later section.

3. RESULTS AND DISCUSSION

Figure 2 showed typical load-deflection curves for the SL specimens with and without nickel coating. The SL specimens without nickel coating deformed 5% at a relatively low load without fracture. In contrast, the deflection curve for the nickel-coated specimens showed a much steep slope, and fracture was observed at a small amount of deflection, varying from 2.7 mm to 4.5 mm, corresponding to a flexural strain of 1.0 – 1.7%. The curve is typical of those for brittle materials. The coating of a thin layer of nickel has dramatically changed the deformation characteristics of the SL resin.

The flexural modulus and the flexural stress at 1% of strain of the coated and uncoated specimens were compared in Figure 3. As shown in Figure 3a, the flexural stress of the SL specimens without nickel-plating is around 21-22 MPa. A thin layer of nickel onto the specimens increased the apparent flexural stress to about 180 MPa, approximately nine folds as high as the substrate material. Similar changes were observed in the apparent flexural modulus (Figure 3b). The average flexural modulus of the SL specimens without nickel coating was around 2.3-2.4 GPa, which is in good agreement with literature data [6]. In contrast, the nickel-coated SL specimens showed an apparent flexural modulus of 18-19 GPa, eight times as high as that of the SL resin. The

building orientation of the specimens, however, showed no obvious effects on either flexural stress or flexural modulus for both coated and non-coated specimens.

The variation of the apparent flexural modulus as a function of the thickness of nickel coating is shown in Figure 4. Within the range of the experiments, the apparent flexural modulus increased linearly with coating thickness. Clearly, the thickness of nickel coating plays an important role in the strengthening effect.

To better understand the strengthening mechanisms of nickel coating, the stress distribution in nickel-coated specimens is analyzed. Because equations (1) and (2) apply only to homogeneous materials, the stress and modulus values calculated using these equations are *apparent* flexural stress and modulus for the nickel-coated specimens. The true stresses in these specimens have to be calculated according to the principles of solid mechanics. From the observation that the nickel coating has a very good adhesion to the SL substrate, the nickel-coated SL specimen can be treated as a single beam made of two materials. For performing the stress analysis, the cross section at the midspan of the nickel-coated specimen, shown in Figure 1, is enlarged and shown in Figure 5A. Under a bending load P at the center of the beam (Figure 1), a flexural strain and stress field is produced along the cross section. By definition, flexural strain is the tensile strain at the outer plane of the specimen normal to the cross section, in the direction of the x-axis in Figure 1. The stress analysis will only be focused on the normal stress on the cross section.

For simple three-point bending deflection, the basic assumption in the flexure theory that planes perpendicular to the beam axis remain planes after flexural deformation is

valid. Therefore, the strain along the x -direction should vary linearly with the distance from the neutral axis of the beam, y , as shown in Figure 5B:

$$\varepsilon_x = k \cdot y \quad (3)$$

where k is a constant and y is the distance from the neutral plane. In the elastic region, the elastic stress is proportional to the Young's modulus of the material:

$$\sigma_{x-Ni} = E_{Ni} \cdot \varepsilon_x \quad (4)$$

$$\sigma_{x-SLA} = E_{SLA} \cdot \varepsilon_x \quad (5)$$

where σ is the elastic stress, E the Young's modulus, and ε_x the tensile strain in the x -direction. The subscripts Ni and SL indicate the corresponding materials. Because the strain varies linearly and continuously across the whole cross section, including the nickel/SL interface, and the Young's modulus is a material constant, the elastic stress should also vary linearly in the same direction within each material. The difference in the Young's moduli of the two materials, however, produces a sharp change in the elastic stress at the SL/nickel interface. The magnitude of the change is equal to the ratio of the Young's modulus of nickel to that of the SL material:

$$\sigma_{x-Ni} / \sigma_{x-SLA} = E_{Ni} / E_{SLA} \quad (6)$$

The stress distribution is schematically illustrated in Figure 5C. Young's modulus of nickel is 20.7 GPa [7] and that of SL polymer is 2.1 GPa [6], respectively. Substituting the numbers into equation (6) yields an elastic stress change by a factor of 10 at the SL/nickel interface. This conclusion is valid for any flexural strain within the elastic region.

For a given flexural strain of 1.0% at the outer surface of the specimen, the elastic strain at the SL/nickel interface can be determined to be 0.96% according to equation (3) and the thickness of the substrate and the coating layer. The minimum and maximum elastic stresses in the SL substrate and in the nickel coating can be easily calculated. In the SL substrate, the minimum elastic stress is zero because the elastic strain is zero at $y=0$. The maximum normal stress in the SL substrate occurred at the SL/Ni interface where the strain is 0.96 %.

$$\begin{aligned}\sigma_{SLA-\max} &= 21000MPa \cdot 0.96\% \\ &= 20.2MPa\end{aligned}$$

The minimum and maximum strain in the nickel layer occurred at the SL/Ni interface and the outer surface, respectively. The corresponding strain value is 0.96% and 1.0%. The minimum and maximum stresses in the nickel-coating layer are then given by:

$$\sigma_{Ni-\min} = 20700MPa \cdot 0.96\% = 198.7MPa$$

and

$$\sigma_{Ni-\max} = 20700MPa \cdot 1.0\% = 207.0MPa$$

The results indicate that the average elastic stress in the nickel-coating layer is 10 times as high as the maximum elastic stress in the SL substrate. This means that for producing a given amount of flexural strain, the nickel-coated specimens requires significant amount of extra load as compared with the SL substrate. In other words, the nickel coating significantly increases the deformation resistance, and therefore produced great strengthening effect.

To examine quantitatively the factors that influence the strengthening effect of the coating layer, the total elastic load carried by the SL substrate, F_{xSL} and that carried by

the nickel coating, F_{xNi} , is examined. By integrating the normal stress with respect to the corresponding cross section areas on one side of the neutral plane, and by keeping in mind that the strain distribution follows equation (3), we get:

$$\begin{aligned} F_{xSL} &= \int_{A_{SLA}} \sigma_x dA = \int_0^{d/2} \varepsilon_x E_{SLA} b^* dy \\ &= k E_{SLA} b d^2 / 4 \end{aligned}$$

Similarly,

$$\begin{aligned} F_{xNi} &= \int_{A_{Ni}} \sigma_x dA = \int_{d/2}^{d/2+\delta} \varepsilon_x E_{Ni} b^* dy \\ &= k E_{Ni} b (d\delta + \delta^2) \end{aligned}$$

Because the coating thickness δ is normally much smaller than the specimen thickness d , the δ^2 term in the parenthesis can be neglected. The load distribution ratio can then be expressed as:

$$F_{xNi} / F_{xSLA} = \frac{4\delta}{d} \cdot \frac{E_{Ni}}{E_{SLA}} \quad (7)$$

This ratio is an indicator for the strengthening effect of the coating layer. A greater ratio means more percentage of the load being carried by the coating layer, hence a greater strengthening effect of the coating. Equation (7) shows that the load distribution ratio depends on two factors. E_{Ni}/E_{SL} represents the effect of the elastic properties of the materials involved. The greater the ratio of the Young's modulus, the greater the strengthening effect. On the other hand, δ/d represents the effect of geometrical factors of the specimens. For a given substrate thickness d , the thicker the coating layer δ , the greater the strengthening effect. If the thickness of the coating is fixed, then the overall

strengthening effect will decrease with increasing substrate thickness. Therefore, strengthening effect will be more significant for thin cross section substrate than for thick cross section ones.

4. CONCLUSIONS

A thin layer of nickel coating significantly changed the flexural properties of the SL polymer. The SL material without nickel coating deflected at relatively low stress up to 5% flexural strain without fracture. With a 0.13 mm surface coating of nickel onto the SL substrate, the apparent flexural modulus and flexural stress increased dramatically, with significantly reduced ductility. The strengthening effect depends on the ratio of the Young's modulus of the substrate to that of the coating materials, and the thickness ratio of the coating layer to that of the substrate material. The greater the Young's modulus ratio, and the greater the coating/substrate thickness ratio, the greater the strengthening effect.

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