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# Investigating the effects of recycling number and injection parameters on the mechanical properties of glass-fibre reinforced nylon 6 using Taguchi method

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ABSTRACT

In this study, the glass-fibre reinforced nylon 6 (PA6-GF) was reprocessed in the five processing cycles. The recycled PA6-GF samples were characterized by its chemical, thermal, and mechanical properties as a function of the number of processing cycles. It was also investigated how the controlled factors affect the output factors and what the optimal injection settings of the controlled factors can be employed to obtain the best mechanical properties. To achieve these aims Taguchi's mixed level parameter design ($L_{18}$) was employed for the experimental design. Number of recycling, melt temperature, mold temperature, injection pressure, and holding pressure were considered as the control factors. Regression analyses were applied to predict tensile strength, yield strength, impact energy and impact strength. Analysis of variance (ANOVA) was used to determine the effects of the control parameters on tensile strength, yield strength, impact energy, and impact strength. In the plastic injection of PA6-GF, the number of recycling was found to be the most effective factor on mechanical properties. From the experimental results it was concluded that there was a decrement in mechanical properties after each reprocessing cycle.



## 1. Introduction

As plastic materials are widely used in recent years, the increasing consumption of plastic material as a consequence of market demand contributes to the large volume of plastic disposal which affects the environment negatively. Since plastic materials are non-degradable, it takes a long time (up to hundreds of years) to break down and disposal of plastics creates space problems. The recycling is one of the most effective methods for diminishing the negative effects of waste plastics on environment. Recycling process reduces both the quantities of plastics sent to landfills and raw material extraction. Recycling process can also contribute to the economy of all countries. Nowadays, recycling process has received immense interest in academic fields. Recycling of polymers has been paid more and more attention, especially for polypropylene (PP), poly(ethylene terephthalate) (PET), polyethylene (PE), polystyrene (PS), acrylonitrile–butadiene–styrene (ABS), and polycarbonate (PC) due to the environmental concerns. However, the recycling process can change mechanical, physical, chemical, and visual properties of plastic.

Nylon (Polyamide-PA) contains the amide repeat linkage in the polymer backbone. PA is a tough, semi-crystalline polymer with a low glass transition and is extensively used in the manufacture of automobile parts and textile fibres due to its high mechanical and impact strength and good processability. There are many types of PA such as PA6, PA12, and PA66. Among them PA6 has a molecular chain made of a base unit with 6 carbon atoms and it is prepared by ring-opening polymerization of ε-caprolactam monomer. PA6 is a high-strength engineering thermoplastic. In general, glass fibre is added to PA6 for improving the stiffness and strength. Glass fibre also has low cost, high chemical resistance and excellent insulating properties. But, excessive wear on molding dies takes place as the hardness of glass fibre is high. The effects of glass fibre on the mechanical properties of virgin PA have been investigated extensively [1–8] and an increase in the mechanical properties with the presence of glass fibre is well known from the literature.

Some studies in the area of recycling of PA are available [9–18]. Eriksson et al. [9] reported an experimental and theoretical study of the mechanical performance of the recycled glass-fibre reinforced polyamide 66. Mechanical properties in an accelerated service-related environment of recycled glass-fibre-reinforced polyamide 66 were reported by Eriksson et al. [1] and polymer reinforced with 30 wt% of short fibres was remolded up to seven times. Eriksson et al. [10] studied the effect of thermal aging on unreinforced and glass-reinforced recycled polyamide 66. Eriksson et al. [11] also studied the effect of in-plant recycling of glass fibre reinforced polyamide 66 and injection molded bars were exposed to thermal aging, coolant aging, and creep testing. In another work Eriksson et al. [12] investigated the effects of impurities on

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mechanical properties of recycled glass fibre reinforced polyamide 66. Lozano-González et al. [13] made a study about multiple recycling of nylon-6 by injection molding on its physical–mechanical properties and morphology in order to understand how many times it is possible to recycle the nylon-6 without significant loss of the properties. Scaffaro and La Mantia [14] evaluated the rheological and the mechanical properties of polymer blends of virgin and recycled polyamide 6 by changing the amount of recycled polymer. Maspoch et al. [15] investigated the effect of the number of reprocessing operations (3 times) and of the fraction of recycled material (15%, 30% and 50%) added to the virgin polymer. Thermal, mechanical (tensile, flexural and impact) and rheological properties of a product of recycled and filled PA6 were reported [15]. The fatigue behaviour of the reprocessed glass fibre reinforced polyamide 6,6 had been studied by Bernasconi et al. [16]. To our knowledge the biggest number of recycling of PA by injection molding was completed by Su et al. [17]. In this study, virgin PA6 was repetitively processed until the 16th cycle. They evaluated mechanical and rheological properties as a function of number of recycling process. After each cycle, they also analyzed the changes in chemical structure, molecular weight, molecular weight distribution, and crystalline behaviour. Goitisolo et al. [18] investigated the effect of reprocessing on the structure and mechanical properties of PA6 based nanocomposites by means of repeated injection molding cycles.

In plastic injection molding, the process parameters such as melt temperature, mold temperature, injection pressure, holding pressure, injection speed, holding time, and cooling time should be optimized to produce plastic products with good mechanical properties. One of the optimization methods is Taguchi method and this method uses orthogonal array, signal-to-noise ($S/N$) ratio and analysis of variance (ANOVA). By using Taguchi's orthogonal array, time and cost required to carry out the experiments can be reduced. Then the experimental results are transformed into the $S/N$ ratio in order to measure the quality characteristics deviating from the desired values. A greater $S/N$ ratio shows better quality characteristics (optimal level of the process parameters). ANOVA is conducted to understand the significant process parameters. Taguchi method has been extensively utilized in engineering area. However, few papers investigate the effect of processing conditions on mechanical properties of recycled plastics using Taguchi method [19–21]. Mehat and Kamaruddin [19] investigated the flexural testing results of recycled PP by adopting the three levels $L_9$ Taguchi orthogonal arrays. Four processing parameters namely melt temperature, packing pressure, injection time, and packing time were considered and number of recycling was not taken into consideration. Mehat and Kamaruddin [20] used Moldflow Plastic Insight (MPI) integrated with $L_{18}$ Taguchi orthogonal array to simulate the significant processing parameters (mold temperature, melt temperature, injection time, packing pressure, packing time, and cooling time) affecting the residual stress of the recycled PP. By incorporating the significant parameters (melt temperature, packing pressure, injection time, and packing time) obtained from the preliminary simulation, $L_9$ Taguchi orthogonal array was utilized to investigate the flexural modulus and stress at yield of the recycled PP. In another study, Mehat and Kamaruddin [21] studied the effects of processing parameters (melt temperature, packing pressure, injection time, and packing time) on the flexural properties of the samples produced from the recycled plastics in various compositions using $L_9$ orthogonal array.

It is necessary to understand the relationship among the various controllable parameters and to identify the important parameters that influence the mechanical properties of recycled polymer. Although there are several studies on recycled PA in the literature, the optimization of injection parameters using recycled glass-fibre reinforced PA is not investigated. Therefore, we report herein how the input parameters and number of recycling influence the output in recycling of glass-fibre reinforced nylon 6 (PA6-GF) by using Taguchi experimental design method, which is the novelty of this study. The possible changes in the chemical structure were tested by fourier transform infrared spectroscopy (FT-IR) measurement. Differential scanning calorimetry (DSC) and thermal gravimetric analysis (TGA) were used to analyse the thermal properties of PA6-GF with reprocessing. The impact fracture surfaces and fibre length of recycled PA6-GF were investigated by scanning electron microscopy (SEM) and polarized optical microscopy (POM), respectively. The effects of structural changes on the mechanical properties were determined by tensile and impact tests.

## 2. Experimental details

### 2.1. Materials

30% Glass-fibre reinforced nylon 6 (Akulon® K224-G6) with a density of 1350 kg/m$^3$ used in this study was obtained from commercial sources, provided by DSM company. Chemical structure of nylon 6 is shown in Fig. 1. 30% glass-fibre reinforced polyamide was coded as PA6-GF through this study. Prior to molding, PA6-GF was dried, for at least 3.5 h, at 80 °C to eliminate air bubbles forming during the injection molding process. Test parts were injected by a plastic injection machine (YIZUMI-UN90A2) which had a maximum clamping force of 900 kN and an injection pressure of 222 MPa. A four-cavity mold (double cavity for tensile specimens and double cavity for impact specimens) was manufactured in the computer numerical control (CNC) machine according to ISO 527 [22] for tensile specimens and ISO 180 [23] for impact specimens standards.

PA6-GF material was recycled five times: 0, 1st, 2nd, 3rd, 4th and 5th. Here 0 refers to virgin PA6-GF. A lot of samples in the form of dumbbell shaped (dog bone) were produced in the injection molding machine. From these, 5 samples were used for the tensile tests of virgin PA6-GF. The remaining plastic was shredded and the regrind material was molded again to produce 1st recycle sample. These procedures were repeated to obtain 2nd, 3rd, 4th and 5th recycled samples.

### 2.2. Taguchi method

Taguchi method uses specially constructed tables known as "orthogonal array" to design experiments. Using of these orthogonal arrays makes the design of experiments very easy and it requires a lesser number of experiments. As a result experimental cost, time, and effort reduce. Using Taguchi's orthogonal array, a total of 486 ($6 \times 3 \times 3 \times 3 \times 3$ for the full factorial design) sets of experiments are reduced to only 18 sets of experiments, thus this means less experimental cost, time and effort. In the current study, Taguchi's mixed level parameter design ($L_{18}$) was used for the experimental design. Number of recycling, melt temperature, mold temperature, injection pressure, and holding pressure were considered as the control parameters. The control factors and their levels are shown in Table 1. The experimental plan for four injection

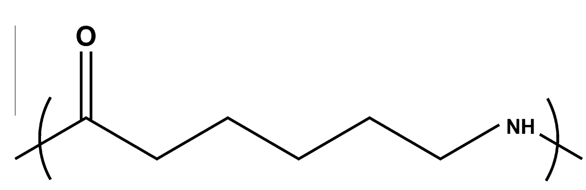


**Fig. 1.** Chemical structure of polyamide (nylon 6).