Int J Plast Technol (December 2012) 16(2):194–209
DOI 10.1007/s12588-012-9037-1

COVER ARTICLE

Quality control and design optimisation of plastic product using Taguchi method: a comprehensive review

Nik Mizamzul Mehat · Shahrul Kamaruddin

Received: 15 March 2011 / Accepted: 21 September 2012 / Published online: 6 November 2012

Abstract The Taguchi method is a powerful approach for solving quality problems in various aspects of the engineering field. Due to the increase of plastic parts consumption in each day, continuing customer satisfaction and economic viability in a competitive plastic industry environment are gaining tremendous attention. Thus, Taguchi method offers a simple yet systematic approach to optimize design for performance, enhancing the product quality and reduce the cost as well. A lot of studies have been conducted on the efficiency of this method. However a total comprehensive review of the implementation of the Taguchi method particularly in the plastic industry is limited. This paper presents an extensive review of past literature on the application of the Taguchi method in plastic industries focusing on product quality enhancing and obtaining the desired properties for new materials. From the review, it can be concluded that the Taguchi method has made extensive contribution to the plastic industry by bringing focused and awareness to robustness to improving quality.

Keywords Taguchi method · Plastic · Quality · Design · Optimization

Introduction

Plastics have become one of the most sought after materials in the world today. Due to its intrinsic advantages of properties such as lightness, resistance to corrosion and ease to shape, plastic has provided an affordable yet robust material for many of the

N. M. Mehat
Department of Mould Technology, Kolej Kemahiran Tinggi MARA Balik Pulau, Genting, 11000, Balik Pulau, Penang, Malaysia
e-mail: nik_miza78@yahoo.com

N. M. Mehat · S. Kamaruddin (✉)
School of Mechanical Engineering, Universiti Sains of Malaysia, Engineering Campus, 14300 Nibong Tebal, Pulau Pinang, Malaysia
e-mail: meshah@eng.usm.my

items people use every day. It can be widely found in many important applications such as clothing, household appliances, automotive parts and even aerospace. Due to this explosive growth of plastic consumption, continuing customer satisfaction and economic practicability in a competitive plastic industry environment are the momentous goals for plastic manufacturers. In order to achieve these goals, the continuous enhancement for both plastic product and process quality and capability at minimal cost are two important elements that should be considered. The establishment of the experiment is the most significant step to improve the product/process quality. Therefore, quality could be designed into the product from the design stage of product or process. Then the quality improvement can be continued through the production phase [1]. According to this fact, therefore, experimental design based on Taguchi methodology is an influential and effective approach in producing good quality plastic products.

Taguchi's approach provides engineers/designers with a systematic and proficient approach for conducting experiments with limited statistical skills to study [2]. In addition, the effects of several processing parameters on the plastic products can be investigated and understood within limited budget and resources [3]. There are a lot of publications relating to this method but no meticulous reviews been documented. Thus, this paper initiatively presents an ample review on the implementation of Taguchi method especially in plastic industries including all past and recent researches or studies carried out. The study will discuss the efficiency of this statistical technique in improving the quality of plastic products and thereby achieving improved material and process performances.

Taguchi method overview

Taguchi method or also known as Robust design has become increasing popular and been utilized widely in enhancing the engineering productivity. This method is a simple and competent method used especially in off-line quality control to design high quality products and determine the optimum setting of the controllable parameters [4–6]. By implementing this method, the best range of designs for quality, performance and computational cost can be determined systematically [7, 8]. This method consists of three stages of system design, parameter design and tolerance design. Of all the three stages of the offline quality engineering system, Taguchi's parameter design is often identified as the most crucial and prevailing stage for process optimization [9, 10]. Parameter design is mainly used to obtain the optimum levels of process parameters for developing the quality characteristics and to determine the product parameter values depending on optimum process parameter values [11]. In general, the parameter design of the Taguchi method utilizes orthogonal arrays (OA), signal to noise (S/N) ratios and analysis of variance (ANOVA). Taguchi's orthogonal arrays are highly fractional orthogonal designs that can be used to estimate main effects using only a few experimental runs. These designs are not only pertinent to two level factorial experiments, but also can investigate main effects when factors have more than two levels or mixed level [4, 7]. It employs a special design of orthogonal arrays such as L_4, L_8, L_{12} and L_{16} to study the whole parameters space with a small number of experiments only. Thus, this method can reduce research and development costs by simultaneously studying a large number of parameters [12, 13]. Moreover, orthogonal arrays also allow researchers or designers to study many design parameters concurrently and can be used to estimate the effects of each factor independent of the other factors [3, 14, 15]. In order to analyze the results, the Taguchi method uses a statistical measure of performance called S/N ratio. The S/N ratio takes both the mean and the variability into account. In Taguchi's method, the term 'signal' represents the desirable value and 'noise' represents the undesirable value. The objective of using the S/N ratio is as a measure of performance to develop products and processes insensitive to noise factors [16]. The S/N ratio indicates the degree of predictable performance of a product or process in the presence of noise factors. The formulae for S/N ratio are designed so that an experimenter can always select the largest factor level setting to optimize the quality characteristic of an experiment. Therefore, the method of calculating the S/N ratio depends on whether the quality characteristic is smaller the better, the nominal the best, and the larger the better [17, 18]. Process parameter settings with the highest S/N ratio always yield the optimum quality with minimum variance. Further understanding on the concept of Taguchi can be found in Taguchi [19], Phadke [20] and Roy [21]. For a better appreciation of the efficacy of this method, the following reviews will reveal the scenario of Taguchi method in enhancing the plastic products or processes quality as well as the material properties.

Taguchi method as a dynamic tool in enhancing the product quality

According to Yang and Gao [22], quality of the product may be characterized in terms of dimensional stability, appearance or an esthetical value and mechanical properties. Recently, the implementation of Taguchi method in improving the plastic product quality produced by a variety of plastic processing techniques including injection moulding (PIM), rotational moulding (RM) and gas assisted injection moulding (GAIM) has gained a remarkable attention among the researchers. The following section will elaborate in detail on the implementation of this method based on these dimensional stability, appearance or an esthetical value and mechanical properties.

Dimensional stability

Dimensional stability is one of the main quality criteria for plastic products. Continuation of the precise shape of the part especially in tight tolerance applications is a major concern among the researchers. However, the occurrence of some defects such as warpage and shrinkage might have influenced the dimensional stability of the plastic product produced. In practice, the defects will be influenced by materials selection [23], mould and part design [24, 25] and processing parameters [26–29]. Minimizing warpage in the product produced is one of the main interests among the researchers as it might affect the dimensional stability of the part. For example, Huang and Tai [30], Liao et al. [31], Ozcelik and Erzurumlu [32], Ozcelik and Sonat [33] used the experimental design of Taguchi method to examine the influential processing parameters over warpage in thin walled parts produced by PIM. The processing parameters studied by the authors including mould temperature, melt temperature, packing pressure, packing time, filling time and injection speed. They have reached the same conclusion where by the packing pressure was found as the most important factor that affects warpage for thin walled part. Even though, Huang and Tai [30] and Ozcelik and Erzurumlu [32], also included the gate location, runner type, filling and cooling time to be studied, but it seems that these factors did not affect the warpage much in thin walled part. On the other hand, focusing on the similar defect which is warpage for thin plate, Tang et al. [34] found that melt temperature is the most significant factor and filling time only slightly influenced on the warpage. More recent works on minimizing the warpage problem in a thin-shell plastic component can be observed from the study carried out by Chen et al. [35]. The authors integrated the application of Moldflow packages with L_{18} orthogonal array to reduce the warpage variation. From the ANOVA results computed, it indicated that the melt temperature and the packing pressure are found to be the most significant controlled parameters in both the simulation and the experimental analysis. Other work by Song et al. [36] investigated the warpage problem in the ultra-thin wall plastic parts. They carried out a research on the influence of different process parameters (i.e. injection rate, injection pressure, melt temperature, metering size and part thickness) on the moulding process of the ultra-thin wall plastic parts. The results showed that part thickness is the decisive parameter to the moulding, metering size and injection rate are the principal factors in moulding process. Melt temperature and injection pressure are the secondary factors, but higher melt temperature and injection pressure are also necessary in the moulding process.

Warpage problem also occurs in the products of gas assisted injection moulding (GAIM). The study carried out by Chen et al. [37] concluded that there four parameters are found to have a great influence on the GAIM product. It is found that a slower gas injection speed, higher melt temperature, higher gas pressure, and longer gas packing time would yield lesser warpage. Other research that related with warpage in GAIM products is carried out by Liu and Chang [38]. The report is devoted to investigate the effects of different processing parameters on the length of gas penetration in thin wall parts. From the findings, it is found that for amorphous acrylonitrile-butadiene-styrene (ABS) materials, the melt temperature and gas pressure are found to be the principal parameters affecting the parts. For semi-crystalline polypropylene (PP) materials, the gas pressure and gas injection delay time are found to be the key processing parameters. In addition, warpage of moulded parts is also found to decrease with the length of gas penetration. Instead of concentrating on the effect of processing parameters on the warpage, the work devoted by Lee and Kim [39] introduced a concept for deliberately varying the wall thicknesses of an injection-moulded part within recommended dimensional tolerance to reduce part warpage using Taguchi method. From the results, it is seen that varying wall thicknesses exhibited better warpage characteristics compared to the constant wall thicknesses.

Instead of PIM, rotational moulding (RM) is one of the most important polymer processing techniques for producing hollow plastic part. However, part warpage caused by inappropriate mould design and processing conditions is the problem that confounds the overall success of this technique. Thus, the report from Liu and Chen [40] has improved the quality of rotationally moulded thermoplastic parts in terms of warpage due to different processing parameters. By conducting Taguchi L_{18} orthogonal array design the part warpage is optimized. They found out that from processing parameters (mould release agent, cooling condition, oven time, oven temperature, mould material, powder size, and pigment) selected, the cooling condition is found to be the principal parameter affecting the warpage of RM product, while the effect of pigmentation is relatively limited.

Warpage also can be associated with the variation of shrinkage. By conducting three level L_{27} and L_9 in the Moldflow packages, Oktem et al. [41] reduced the warpage problems that are related to a variation in the process parameters dependent on the shrinkage. Based on the ANOVA results, it is apparent that packing pressure is the most important parameter with a percent value of 58.03 % on warpage followed by packing pressure time of 23.03 %, injection time of 15.17 % and cooling time of 3.68 %, respectively. They also have improved 2.17 % and 0.7 % of warpage and the shrinkage respectively by determining the optimal processing parameters. The warpage induced during the moulding process as a result of differences in the shrinkage of the constituent materials also become a critical issue in electronic industry. Teng and Hwang [42] applied Taguchi method to identify the relative influences of the transfer pressure, the packing pressure, the mould temperature and the curing time on the degree of package warpage and established the optimal processing conditions. The results demonstrated the capability of Taguchi processing parameters on the basis of a limited number of simulation runs. On the other hand, Erzurumlu and Ozcelik [43] conducted an experiment to reduce warpage and sink index problem in the part produced. They studied the effect of processing parameters including mould temperature, melt temperature, packing pressure together with different rib cross-section types and rib layout angle. From the S/N ratio and ANOVA results, they concluded that for the different types of thermoplastic materials, the effects of mould and melt temperature, packing pressure and rib cross-section types and rib layout angle respectively have different impact on warpage and sink index.

In acknowledging on the importance of controlling the part shrinkage independently especially in applications that requires tight tolerances, numerous advanced investigations have been carried out. For example, Chang and Faison [44] applied Taguchi method to systematically investigate the effects of processing parameters on the shrinkage behaviour (along and across the flow directions) of three plastic materials. The results from the research shown that the mould and melt temperature, along with holding pressure and holding time, are the most significant factors to the shrinkage behaviour of the three materials, although their impact is different for each material. In corresponding to work done by Chang and Faison [44], by adopting a similar design of experiment method and ANOVA analysis, Altan [45] determined the effects of melt temperature, injection pressure, packing pressure and packing time on the shrinkage of injection moulded polypropylene (PP) and polystyrene (PS). From the S/N ratios results, 260 °C of melt temperature, 60 MPa of injection pressure, 50 MPa of packing pressure and 15 s of packing time will give a minimum shrinkage of 0.937 % for PP and 1.224 % for PS. Statically the most significant parameters are found to be the packing pressure and melt temperature for the PP and PS mouldings respectively. Other work focusing on similar quality characteristic can be found in Huang et al. [46]. The Taguchi method is utilized to investigate the effects of six processing parameters, including mould temperature, compression speed, compression time, compression distance, delay time, and compression force, on part shrinkage uniformity (SU). The results showed that the compression force is the most important parameter for SU of both polypropylene (PP) and amorphous polystyrene (PS) parts. On the other hand Wu and Su [47] compared the shrinkage of two moulding methods which are PIM and injection compression moulding (ICM) based on the optimum processing parameters that obtained from Taguchi Method. The process parameters studied are injection velocity, melt and mould temperatures, the packing pressures, the packing period, the cooling time and mould open distance. The results showed that the packing pressure strongly affects the shrinkage for PIM product. For ICM, mould temperature, melt temperature and injection velocity were three factors that affected the shrinkage most significantly. Another work relating with ICM product can be viewed in Liu and Lin [48]. The effects of processing parameters including melt temperature, mould temperature, melt filling pressure, short shot size, packing pressure, compression pressure and cooling time are investigated on the dimensional quality of moulded parts. They concluded that the short shot size and melt temperature are found to be the principal parameters affecting the dimensional accuracy of moulded parts. The findings can be used to optimize the moulding process.

Concentrating on the similar quality characteristic which is dimensional accuracy, the work by Ong and Koh [49] on the other hand, found out that the significant factors affecting the micro parts are mould temperature followed by injection pressure and injection rate. In corresponding to work done by the previous authors, Kuo et al. [50] promoted the accuracy and reduced the dimension deviation of PIM product by the Taguchi method and the Back Propagation Neural Network (BPNN). They have optimized the processing parameters using the most precursory material, Polyether Ether Ketone (PEEK). Compared to the other researchers, Galantucci and Spina [51] studied the bulk temperature, shear stress, cavity pressure at end of filling, maximum clamping force, maximum volumetric shrinkage and maximum sink index of thermoplastic injection moulded parts in FE simulation by integrating the Taguchi L_8 orthogonal array. The influence of gating system in optimizing the filling conditions of the part is the main focus. Through data integration between the FE analysis and the Design of Experiment approach, the filling of part with complex geometries is studied to optimize injection process parameters and improve the product quality.

Appearance or aesthetical value

As being highlighted before, the appearance or the esthetical value is one of the vital criteria in producing plastic product. Many of the products produced are rejected due to the aesthetic quality. One of the defects which might affect the esthetical value of the plastic product and frequently occur in injection moulded part is silver streaks or splay problem. From the study carried out by Chen et al. [52], the silver streaks problem that appeared on the surface of polycarbonate/poly(butylene terephthalate) automobile bumper can be improved by applying the Taguchi method. The authors conducted a preliminary and principal experiment with L_{12} and L_{18} orthogonal array respectively. From the optimization process, the results revealed that the main factors that directly relate to the generation of silver streaks are the mould temperature, fill time, fill/post fill switch over control, and injection rate.

Another defect that also been distinguished as one of the defects that might affect the esthetical value of the product produced is weld line. Weld-lines or knit-lines are formed during the mould filling process when the split melt flow fronts meet at the same downstream location and look like cracks on the appearance of plastic products. Sometimes these visible features are not accepted aesthetically in many applications. However, most importantly, the local mechanical strength in the weld-line area could be significantly weaker. Hence, how to prevent the weld-lines and guarantee the good quality are the major concerns to part/mould designers. For example, Liu and Yang [38] conducted L_{18} experimental matrix design based on the Taguchi method to study the effect of different processing parameters such as melt temperature, mould temperature, melt filling speed, melt filling pressure, packing pressure, and size of the obstacle on the weld line strength of PIM product. For the factors selected in the experiments, sizes of obstacle and melt temperature are found to be the important parameters affecting the weld line strengths of injection-moulded composites.

Another work focused on weld line can be viewed in Xie and Ziegmann [53]. They investigated the relation between weld line strength in micro injection moulding parts and processing parameters. The results showed the significant parameters are mold temperature, melt temperature, injection speed, ejection temperature, packing pressure and injection pressure. Apart of silver streak and weld line, the surface quality (part roughness) problem in GAIM product also gained attention among the researchers. For example, Liu and Chang [54] conducted an L_{18} experimental matrix design to optimize the surface quality (part roughness) of 35 % glass fibre reinforced Nylon-6 composite. For the factors selected in the main experiments, melt temperature and gas injection delay time are found to be the principal factors affecting the surface quality of the product. On the other hand, selecting light transmission, surface waviness and surface finish as the quality characteristics, Tsai et al. [55] performed screening experiments to identify the important significant process parameters affecting quality of lenses during the injection moulding process. From the results of Taguchi method, it shown that the most significant process parameters affecting surface waviness of lenses are packing pressure and melt temperature followed by injection pressure and mould temperature. However, the processing parameters selected are found to have little effect on light transmission and surface finish of lenses.

Another defect occurs in the injection moulded part is sink mark. A sink mark is a local surface depression that typically occurs in moulding with thicker sections, or at location above ribs, bosses, and internal fillets. These defects are caused by localized shrinkage of the material at thick section without sufficient compensation when the part is cooling. The work done by Shen et al. [56] minimized this defect in the injection moulded parts by conducting the Taguchi L_{18} OA. They found out that the part thickness, holding pressure, melt temperature and mould temperature are the principal factors affecting the sink marks of the injection moulded parts. Another work in minimizing sink mark problem in PIM product can be viewed in Wang et al. [57]. For the factors and interactions selected in the main experiments, the boss thickness and melt temperature are found to be the principal factors affecting sink mark formation in injection-moulded parts.

Mechanical properties

As stated by Yang and Gao [22], mechanical properties is one of the crucial criteria that need to be considered in producing plastic product. The product produced should perform certain mechanical requirements depending on the functions of the product itself. The plastic products that perform the mechanical requirements needed ensure the improvement and continuity in product reliability and maintainability during the product service. Enhancing the mechanical properties of the product produced has been investigated from several aspects in the literature. For example, Liu et al. [58] optimized the impact strength of RM product through processing parameters such as oven temperature, oven time, cooling condition, mould material and particle size by Taguchi L_{16} orthogonal array. The results of the statistical analysis indicated that the oven temperature and oven time are the principal factors affecting the impact property of the product.

Focusing on tensile strength on the ultra-high molecular weight polyethylene (UHMWPE) of an injection moulded part, Kuo and Jeng [59] also discussed the effect of various processing parameters on this mechanical properties. By adopting the three level L_{18} Taguchi orthogonal arrays in conducting the experiment, the effects of melt temperature, mould temperature, injection velocity, packing pressure, packing time and cooling time together with cross-sectional dimensions on tensile strength are investigated in line with weld line strength. From the findings, they concluded that cross-sectional dimensions cause a higher effect on the tensile strength than the processing parameters do for the UHMWPE specimen without weld line. For the case of sample with weld line, the effects of processing parameters and cross-sectional dimension have been reduced by the presence of that weld line.

Apart of that, Yang et al. [15] analyzed contour distortions, wear mass losses and tensile properties of polypropylene (PP) composites components applied to the interior coffer of automobiles. Nine controlling factors with two levels for each factor are selected including melting temperatures, injection speeds, and injection pressures via three computer-controlled progressive strokes. Choosing the largest possible S/N ratio then an optimal process parameter level/factor combination is identified. Taken the ultimate stress measured by tensile test serves as an indicator of the part quality, the effects of process variables, including injection pressure, mould opening distance, resin temperature, compression pressure, pre-heated mould temperature, and cure temperature on the quality of compression resin transfer moulding (CRTM) product are investigated. This work can be viewed in Chang et al. [60]. Experimental result showed that the compression pressure and the resin temperature are significant variables for improvements in the mechanical properties of the part, while the effect of pre-heated mould temperature on the mechanical properties appears to be trivial.

Other work relating with ultimate stress can be further viewed in Fung and Tien [61]. They investigated ultimate stress and fracture toughness for injection-moulded 30 wt.% glass fibre-reinforced poly(butylene terephthalate) (PBT) using Taguchi Method and grey relational analysis. The results presented the characteristics of the Taguchi method as a very powerful tool for single-response problems. On the other hand, Kim et al. [62] optimized the manufacturing parameters of a brake lining for moulding and heat treatment to improve friction stability and wear resistance using the parameter design proposed by the Taguchi analytical methodology. They applied the method to find affective parameters to control physical properties (surface hardness and porosity) of a brake lining and to achieve optimal manufacturing conditions for improved brake performance. The findings showed that the moulding pressure and the moulding temperature are dominant manufacturing parameters for surface hardness and porosity, respectively. Corresponding to the work of Kim et al.

[62], focusing on friction properties of the moulded part, Fung and Kang [63] investigated the influence of injection moulding processing parameters on the mechanical properties of the product. L_9 Taguchi orthogonal array are used to lay out all the experiments. The results of ANOVA showed that from all four controllable factors of filling time, melt temperature, mould temperature and ram speed, the melt temperature and ram speed are the most important factors to the P-type and A-P type friction coefficient respectively.

Liu and Chang [64] conducted an L_{18} orthogonal array design to optimize the joint strength of ultrasonically welded thermoplastic composites. They found that the amplitude of vibration, hold time and geometry of the energy directorsare are the principal factors affecting the joint property of ultrasonically welded nylon composites. Semicircular energy directors are also found to weld products of the highest strength. In addition, the joint strength of the parts increases with the fibre content in the composites, but decreases with the moisture of the materials. The work carried out by Altan and Yurci [65], focused on the optimization of the injection moulding process parameters to minimize thermal residual stresses in the surface regions of the polystyrene and high density polyethylene parts. From the ANOVA result, the most important parameters for residual stresses in surface regions of the PS and HDPE parts are melt temperature and mould temperature, respectively.

In spite of enhancing the mechanical properties of the product produced, many researchers also gave tremendous attention in designing material with desired properties especially in relating with mechanical properties by adopting the Taguchi method. The following review will discuss the practicality of this method in conducting an experiment thereby the new materials with tailored properties can be produced.

Taguchi method as a dynamic tool in enhancing the material properties

The emergence of plastic material to substitute metal and wood in producing a wide range of applications including automobiles, buildings and even aerospace, the research and development of the material especially in designing the desired properties and performances enhancement has gained a remarkable attention among the researchers. The Taguchi method is well recognized and widely used as design of experiment in order to produce the tailored properties of the material especially in relating with mechanical properties. For a better appreciation of the implementation of this method in enhancing the material properties, this paper will particularly discuss the mechanical properties of the materials in terms of mechanical behaviour under load, relative motion in contact and fibre orientation point of views.

Mechanical behaviour under load

Recently, many works are devoted in investigating the behaviour of materials especially in relating with mechanical behaviour under load. The study of polymer structure and its behaviour under load has become successful in determining the structural elements pertaining to the deformation and strength properties of polymers. For example, the work carried out by Dong and Bhattacharyya [66] focused on the effects of clay type and content, maleated PP (MAPP) content and PP type on the mechanical properties of polypropylene/organoclay nanocomposites. The injection moulded samples are prepared for mechanical testing by adopting the three level L_9 Taguchi orthogonal arrays. In order to maximize tensile/flexural moduli and strength and impact strength of prepared nanocomposite, the authors selected the larger-the-better characteristics in analysing the S/N ratios. From the ANOVA results, they concluded that PP grade has the most significant effect on the overall improvements of mechanical properties and as somewhat expected, PP with the lowest viscosity shows the best performance. In addition, clay content is detected as the second significant factor to enhance the tensile and flexural properties. However, clay type and MAPP content are two non-significant factors found in this study except that MAPP content has greater influence on the impact properties of nanocomposites. The work done by Sureshkumar et al. [67] also focused on the similar tensile strength and impact strength for the blends of linear low density polyethylene (LLDPE) and poly dimethyl siloxane rubber (PDMS). They optimized the processing parameters such as temperature, rotor speed and time in an internal mixer by Taguchi method. The optimum processing parameters are found to be a temperature of 200 °C, a rotor speed of 100 rpm and the time as 8 min. Other work carried out by Xin et al. [68] conducted an experiment using microcellular injection-moulded polypropylene (PP)/waste ground rubber tire powder blend (WGRT) based on Taguchi three levels L_9 orthogonal arrays. They studied the effects of the melt temperature, chemical foaming agent (CFA) by weight, shot size and injection speed on the mechanical properties and microstructures of the samples blend. From the S/N ratio analysis, among the four moulding parameters studied, the CFA weight percentage appears to be the most pre-dominant moulding parameter affecting the cell size, cell density and tensile strength in microcellular blend.

Other researchers, Hafezi et al. [2] investigated the physicomechanical properties including tensile strength, elongation at break, hardness, resilience and aging of acrylonitrile butadiene rubber-poly vinyl chloride (NBR-PVC) blend cured by sulphur and electron beam. For sulphur curing stage, an L_9 orthogonal array is applied to determine the effect of three process parameters on physicomechanical properties. Results showed that the physicomechanical properties, except resilience, of NBR–PVC blend cured by the electron beam improved by 15 % compared with blends cured by the sulphur system. Other work by Yang [69] analyzed the mechanical properties of polycarbonate (PC) reinforced with 20 % short glass fibre (SGF) and 6 % polytetrafluoroethylene (PTFE), which is applied to the bottom cover of the reader body. The author conducted nine experimental runs based on the orthogonal arrays to determine the optimum factor level conditions. The findings concluded that the melt temperature is the most influenced factor in the Young's module, ultimate stress and strain for the injection moulding process.

A part of that, the effect of polypropylene fibre and silica fume on the mechanical properties of lightweight concrete exposed to high temperature are the main focus in the work of Tanyildizi [70]. From the ANOVA results, of the three control factors (silica fume percentage, polypropylene fibre percentage and high temperature degree), the most effective parameters on the mechanical properties of lightweight concrete are found as heating degree. Focusing on yield stress and elongation of polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS) blending, Fung et al. [71], proposed the grey relational analysis based on Taguchi method's orthogonal array to study the effect of injection moulding process on the blending. The findings recommended the factor level combination of filling time at 6 s, melt temperature at 260 °C, mould temperature at 65 °C and ram speed at 100 %. The melt temperature is found as the most influential factor to mechanical properties of both yield stress and elongation.

Mechanical behaviour under relative motion in contact

Another issue that drew an enormous attention among researchers is the occurrence of the defects due to the relative motion in contact materials. The relative motion in contact not only generates defects in material but also degradation in polymer structure and its behaviour especially relating with mechanical properties. One of the examples of the defects due to this relative motion in contact is erosive wear. Focusing on the erosive wear behaviour of polyester matrix composites, Patnaik et al. [72] investigated the influences of impact velocity, fibre loading, stand-off distance, impingement angle and erodent size in accordance with L_{27} (3^{13}) orthogonal array design on the quality characteristic. The findings of the experiments indicated that the erodent size, fibre loading, impingement angle and impact velocity are the significant factors in a declining sequence affecting the wear rate. By using Taguchi optimization approach the erosive wear behaviour of this material can be minimized. With the similar characterization which is erosive wear, another work by Patnaik et al. [73] focused on the effect of glass fibre reinforcement and inclusion of SiC filler on the same material. Using L_{27} Taguchi orthogonal array to conduct the experiments, they concluded that factors like erodent size, SiC percentage, impact velocity and impingement angle, in order of priority, are significant to minimize the erosion rate. The next work also by Patnaik et al. [74], studied the potential of alumina as filler in glass fibre-reinforced polyester composite. They investigated the effect of alumina filling on the erosion wear performance utilizing an air jet type erosion test configuration and the Taguchi orthogonal array approach. The study showed that pure glass-polyester composite without filler shows greater erosion rate whereas a significant improvement in the erosion resistance is observed with alumina fillers. Focusing on the same characterization, further study that carried out by Patnaik et al. [75] investigated the potential of flyash, an industrial waste as a filler material in polyester matrix composites. Using similar Taguchi orthogonal array to study specifically the solid particle erosion characteristic of this flyash filled glass fibre reinforced polyester composites under various experimental conditions; they found out that flyash percentage is the most significant factor in minimizing the erosion rate.

On the other hand, delamination, or interfacial crack, which is one of the most common modes of failure, occurs in composite materials due to the same phenomenal. The work done by Pelegri and Tekkam [76] minimized this problem by evaluating main and interactive factor effects on mode I critical delamination fracture toughness (GIC) in cross ply graphite-epoxy laminates using Design of Experiments together with Taguchi arrays. The factors studied are design and material criteria (width, length, thickness of specimen, delamination length and stacking sequence). Another work by Fung [77] studied the wear volume losses of fibre-reinforced polybutylene terephthalate in different sliding directions. By adopting the grey relational analysis based on Taguchi method's orthogonal array, the results showed that the melt temperature is found to be the most influential factor in both wear volume losses of different sliding directions. Apart of that, Geng and Laborie [78] improved the fibre/matrix interfacial adhesion and the resistance to creep of the matrix by silane chemistry for wood/plastic composites (WPCs). They evaluated the impact of vinytrimethoxysilane content (VTMS), dicumyl peroxide content (DCP), and the processing temperature on the rheological, morphological, and dynamic mechanic properties of WPCs by implementing the Taguchi method. From the results, the rheological properties are significantly impacted by the VTMS content and temperature. A larger depression in LDPE melting point and crystallinity index when a high VTMS content (35 phr), high DCP content (o.5 phr) and a high compounding temperature (200 °C) were used. Whereby, higher dynamic mechanic properties in WPCs with higher content in silane reactants.

Mechanical behaviour under fibre orientation

It has been demonstrated that the material properties are strongly dependent on the fibre orientation within the polymer matrix [79, 80]. Chang et al. [81] optimized the fibre orientation of polycarbonate reinforced with 20 wt.% and 30 wt.% short glass fibre matrix composite by adopting Taguchi method and CAE simulation analysis. They found that the fibre orientation is perpendicular with flow direction in frozen layer and core layer, while it is parallel with flow direction in shear layer. A part of that, Xian et al. [82] studied the effect of selected impregnation parameters on a glass fibre (GF) roving reinforced polypropylene (PP) tape that is prepared with a pin-assisted-melt impregnation process. From the Taguchi optimization, the results indicated that pulling speed, melt temperature and the number of impregnation pins are the significant factors in a declining sequence affecting the impregnation process. Moreover, roving pretension, considered as an insignificant factor that did not affect the average and the variation at all. Other work by Jalili et al. [83] optimized different agitation rates, suspending agent and aqueous phase initiator concentrations as well as emulsifier amounts in order to reach a desired bead size of styrene (St)/methyl methacrylate (MMA) using the Taguchi method. They concluded that final bead size in MMA/St suspension polymerization significantly affected by the presence of n-pentane for all quality characteristic selected in the study.

From all the reviewed works, the findings will be included in order to give a better appreciation of the implementation of the Taguchi method in controlling, designing and optimizing the plastic product quality and enhancing the properties of the materials. This will be highlighted in the next subsequent section.

Summary of the literature review

Plastic industries particularly, the tremendous attention is given particularly in enhancing the product quality and designing the desired properties in a composite material. Most focus is given in minimizing the warpage and shrinkage problems especially in thin-walled plastic products in various plastic processing techniques. In the appearance or esthetical values point of view, there are studies on silver streak, weld line, surface quality and sink mark. As for the mechanical properties of the product produced, enhancing this criterion has been investigated from several aspects in the literature including impact and tensile strength, ultimate stress, friction properties, wear behaviour and joint strength. From the extensive literature survey conducted, many researchers have adopted the Taguchi method rather than depending on trial-and-error method. To satisfy the volatile nature of today's demand on plastic products, the conventional method as trial and error, which depends on the experiences and intuition to control the quality of the plastic parts, is costly, time consuming and not optimal for complex manufacturing processes. The continuous enhancement for both plastic product and process quality and capability at minimal cost are two important elements that should be considered. Therefore, the Taguchi method was recognized as a well versed approach to be adopted. Many of the researchers adopted this method in designing their experiment due to the effectiveness, systematic approach and also limited statistical skills to study.

By adopting the Taguchi method, many of the product quality problems due to materials selection, mould and part design and processing parameters can be minimized. By utilizing the S/N ratios and analysis of variance (ANOVA) offered by Taguchi method, the factors that contribute to the occurrence of the defects in plastic product can be optimized and the influence of each factor can be identified. Part from that, the findings also revealed the efficiency of Taguchi method in designing the properties desired for composite materials through experiment. The Taguchi orthogonal arrays are mostly employed to substitute the conventional full-factorial experimental design in order to run the experiment. This is due to implementation of Taguchi orthogonal array (OA) in reducing the large number of experiment. This, in turn, will have a significant impact on the time consumed as well as the overall costs of conducting the experiments. However, most research based on Taguchi method has been concerned with optimizing only a single response or quality characteristic. This drawback of Taguchi method is not appropriate with today's complex manufacturing processes which deal with multi-responses or quality characteristics. In order to optimize these multi-responses or quality characteristics concurrently, the Taguchi method should be integrated with other method such as regression technique, principal component analysis (PCA) and Grey relational analysis (GRA).

Conclusion

According to the findings of this literature review, it can be concluded that the Taguchi method is an efficient and simple methodology in producing high quality products, minimizing the occurrence of the defects in the product produced as well as designing desired properties in new material. This statistical design of experiment focused on eliminating the cause of poor quality and making the product performance or the process insensitive to the variation in small number of experiment with limited statistical skills to study.

Acknowledgement The authors acknowledge the Short term Research Grant provided by Universiti Sains Malaysia, Pulau Pinang for the funding of the study which has resulted in this article.

References

1. Feigenbaum AV (1991) Total quality control, 3rd edn. McGraw Hill Inc, New York
2. Hafezi M, Nouri Khorasani S, Ziaei F, Azim HR (2007) Comparison of physicomechanical properties of NBR—PVC blend cured by sulfur and electron beam. J Elast Plast 39:151
3. Antony J, Kaye M (1999) Experimental quality- a strategic approve to achieve and improve quality. Kluwer Academic Publishers, Dordrecht
4. Ross PJ (1996) Taguchi techniques for quality engineering. McGraw-Hill, New York
5. Packianatheri MS, Drakei PR, Rowlands H (2000) Optimizing the parameters of multilayered feed forward neural networks through Taguchi design of experiments. Quali Relia Eng Inter 16:461–473
6. Anthony J, Perry D, Wang C, Kumar M (2006) An application of Taguchi method of experimental design for new product design and development process. Assem Autom 26(1):18–24
7. Taguchi G (1990) Introduction to quality engineering. Mc Graw-Hill, New York
8. Peace GS (1993) Taguchi methods: a hands-on approach. Addison-Wesley, Reading, MA
9. Kim YJ, Cho BR (2000) Economic consideration on parameter design. Quali Relia Eng Inter 16:501–514
10. Antony J (2001) Simultaneous optimisation of multiple quality characteristics in manufacturing processes using Taguchi's quality loss function. Inter J of Adv Manuf Tech 17:134–138
11. Yong WH, Tarng YS (1998) Design optimization of cutting parameters for turning operations based on Taguchi method. J Mat Process Tech 84:122–129
12. Ghani JA, Choudhury IA, Hassan HH (2002) Application of Taguchi method in the optimization of end milling parameters. J Mat Process Tech 145:84–92
13. Montgomery DC (2001) Design and analysis of experiments, 5th edn. John Wiley & Sons, Inc
14. Foster WT (2000) Basic Taguchi design of experiments. In: National Association of Industrial Technology Conference, Pittsburgh, PA
15. Yang YK, Shie JR, Liao HT, Wen JL, Yang RT (2008) A study of taguchi and design of experiments method in injection molding process for polypropylene components. J of Reinf Plast and Comp 27:819
16. Chen YH, Tam SC, Chen WL, Zheng HY (1996) Application of Taguchi method in the optimization of laser micro-engraving of photomasks. Inter J Mat Prod Tech 11(3/4):333–344
17. Kwah JS (2005) Application of Taguchi and response surface methodologies for geometric error in surface grinding process. Inter J Mach Tools Manuf 45:327–334
18. Wu Y, Wu A (2000) Taguchi methods for robust design. The American Society of Mechanical Engineers, The Park Avenue, New York
19. Taguchi G (1986) Introduction to quality engineering. Asian Productivity Organisation, Tokyo
20. Phadke MS (1989) Quality engineering using robust design. Prentice-Hall, Englewood cliffs, NJ
21. Roy RK (1990) A primer on the Taguchi method. Van Nostrand Reinhold, New York
22. Yang Y, Gao F (2006) Injection molding product weight: online prediction and control based on a nonlinear principal component regression model. Polym Eng Sci 46(4):540–548
23. Budinski KG (1996) Engineering materials: properties and selection, 5th edn. Prentice-Hall, New Jersey
24. Sanjeeva MN, Kagan VA, Bray RG (2003) Optimizing the mechanical performance in semi-crystalline polymers: roles of melt temperature and skin-core crystalline morphology of nylon. J Reinf Plast Comp 22:685
25. Li CG, Li CL (2008) Plastic injection mould cooling system design by the configuration space method. Comp-Aid Desig 40(3):334–349
26. Chien RD, Chen SC, Lee PH, Huang JS (2004) Study on the molding characteristics and mechanical properties of injection-molded foaming polypropylene parts. J Reinf Plast Comp 23(4):429–444
27. Ismail H, Suryadiansyah (2004) A comparative study of the effect of degradation on the properties of PP/NR and PP/RR blends. Polym-Plast Tech Eng 43(2):319–340
28. Lin YH, Deng WJ, Huang CH, Yang YK (2008) Optimization of injection molding process for tensile and wear properties of polypropylene components via Taguchi and design of experiments method. Polymer–Plastics Technology Engineering 47(1):96–105
29. Chen WC, Tai PH, Wang MW, Deng WJ, Chen CT (2008) A neural network-based approach for a dynamic quality predictor in plastic injection molding process. Exp Syst with Appl 35(3):843–849
30. Huang MC, Tai CC (2001) The effective factors in the warpage problem of an injection molded part with a thin shell feature. J Mat Process Tech 110(1):1–9
31. Liu SJ, Chang CY (2003) The influence of processing parameters on thin-wall gas assisted injection molding of thermoplastic materials. J Reinf Plast Comp 22(8):711–731
32. Ozcelik B, Erzurumlu T (2006) Comparison of the warpage optimization in the plastic injection molding using ANOVA, neural network model and genetic algorithm. J Mat Process Tech 171:437–445

33. Ozcelik B, Sonat I (2009) Warpage and structural analysis of thin shell plastic in the plastic injection molding. Mat Desig 30:367–375
34. Tang SH, Tan YJ, Sapuan SM, Sulaiman S, Ismail N, Samin R (2007) The use of Taguchi method in the design of plastic injection mould for reducing warpage. J Mat Process Tech 182:418–426
35. Chen CP, Chuang MT, Hsiao YH, Yang YK, Tsai CH (2009) Simulation and experimental study in determining injection molding process parameters for thin-shell plastic parts via design of experiments analysis. Exp Syst App 36:10752–10759
36. Song MC, Liu Z, Wang MJ, Yu TM, Zhao DY (2007) Research on effects of injection process parameters on the molding process for ultra-thin wall plastic parts. J Mat Process Tech 187–188:668–671
37. Chen CS, Cheng WS, Wang TS, Chien RD (2005) Optimum design of gas-assisted injection molding. J Reinf Plast Comp 24:1577
38. Liu SJ, Yang CY (2004) Application of statistic estimation to weldline strength of injection molded termoplastic composite. J Reinf Plast Comp 23:1383
39. Lee BH, Kim BH (1997) Variation of part wall thicknesses to reduce warpage of injection-molded part: robust design against process variability. Polym-Plast Tech Eng 36(5):791–807
40. Liu SJ, Chen CF (2002) Significance of processing parameters on the warpage of rotationally molded parts. J Reinf Plast Comp 21:723
41. Oktem H, Erzurumlu T, Uzman I (2007) Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part. Mat Desig 28:1271–1278
42. Teng SY, Hwang SJ (2007) Predicting the process induced warpage of electronic packages using the P–V–T–C equation and the Taguchi method. Micro Relia 47:2231–2241
43. Erzurumlu T, Ozcelik B (2006) Minimization of warpage and sink index in injection-molded thermoplastic parts using Taguchi optimization method. Mat Desig 27(10):853–861
44. Chang TC, Faison E (2001) Shrinkage behavior and optimization of injection molded parts studied by the Taguchi method. Polym Eng Sci 41:703–710
45. Altan M (2010) Reducing shrinkage in injection moldings via the Taguchi, ANOVA and Neural Network methods. Mat Desig 31:599–604
46. Huang HX, Li K, Li S (2009) Injection-compression molded part shrinkage uniformity comparison between semicrystalline and amorphous plastics. Polym-Plast Tech Eng 48(1):64–68
47. Wu CH, Su YL (2003) Optimization of wedge-shape parts for injection molding and injection compression molding. Int Comm Heat Mass Trans 30(2):215–224
48. Liu SJ, Lin KY (2005) Injection compression molding of wedge-shaped plates: effects of processing parameters. J Reinf Plast Comp 24:373
49. Ong NS, Koh YH (2005) Experimental investigation into micro injection molding of plastic part. Mat Manuf Process 20(2):245–253
50. Kuo CFJ, Su TL, Li YC (2007) Construction and analysis in combining the taguchi method and the back propagation neural network in the PEEK injection molding process. Polym-Plast Tech Eng 46 (9):841–848
51. Galantucci LM, Spina R (2003) Evaluation of filling conditions of injection moulding by integrating numerical simulations and experimental tests. J Mat Process Tech 141:266–275
52. Chen RS, Lee HH, Yu CY (1997) Application of Taguchi's method on the optimal process design of an injection molded PC/PBT automobile bumper. Comp Struc 39(3–4):209–214
53. Xie L, Ziegmann G (2009) Influence of processing parameters on micro injection molded. Micro Tech 15:1427–1435
54. Liu SJ, Chang JH (2000) Application of the Taguchi method to optimize the surface quality of gas assist injection molded composites. J Reinf Plast Comp 19:1352
55. Tsai KM, Hsieh CY, Lo WC (2009) A study of the effects of process parameters for injection molding on surface quality of optical lenses. J Mat Process Tech 209:3469–3477
56. Shen C, Wang L, Cao W, Qian L (2007) Investigation of the effect of molding variables on sink marks of plastic injection molded parts using Taguchi DOE Technique. Polym-Plast Tech Eng 46(3):219–225
57. Wang L, Li Q, Shen C, Lu S (2008) Effects of process parameters and Two-Way interactions on sink mark depth of injection molded parts by using the design of experiment method. Polym-Plast Tech and Eng 47(1):30–35
58. Liu SJ, Lai CC, Lin ST (2000) Optimizing the impact strength of rotationally molded parts. Polym Eng Sci 40(2):473–480
59. Kuo HC, Jeng MC (2010) Effects of part geometry and injection molding conditions on the tensile properties of ultra-high molecular weight polyethylene polymer. Mat and Desig 31(2):884–893

60. Chang CY, Hourng LW, Chou TY (2006) Effect of process variables on the quality of compression resin transfer molding. J of Reinf Plast and Comp 25:1027
61. Fung CP, Tien YF (2005) Study of multiresponse optimization for fiber-reinforced poly(butylene terephthalate). J of Reinf Plast and Comp 24:923
62. Kim SJ, Kim KS, Jang H (2003) Optimization of manufacturing parameters for a brake lining using Taguchi method. J of Mat Process Tech 136:202–208
63. Fung CP, Kang PC (2005) Multi-response optimization in friction properties of PBT composites using Taguchi method and principle component analysis. J of Mat Process Tech 170:602–610
64. Liu SJ, Chang IT (2002) Optimizing the weld strength of ultrasonically welded nylon composites. J of Comp Mat 36:611
65. Altan M, Yurci ME (2010) Optimization of residual stresses in the surface regions of injection moldings. Polym-Plast Tech and Eng 49(1):32–37
66. Dong Y, Bhattacharyya D (2008) Effects of clay type, clay/compatibiliser content and matrix viscosity on the mechanical properties of polypropylene/organoclaynanocomposites. App Sci and Manuf 39 (7):1177–1191
67. Sureshkumar MS, Naskar K, Nando GB, Bhardwaj YK, Sabharwal S (2008) Optimization of process parameters of immiscible blends of linear low-density polyethylene and poly dimethyl siloxane rubber using Taguchi methodology. Polym-Plast Tech and Eng 47(4):341–345
68. Xin ZX, Zhang ZX, Pal K, Byeon JU, Lee SH, Kim JK (2010) Study of microcellular injection-molded polypropylene/waste ground rubber tire powder blend. Mat and Desig 31:589–593
69. Yang YK (2006) Optimization of injection molding process for mechanical properties of short glass fiber and polytetrafluoroethylene reinforced polycarbonate composites: a case study. J of Reinf Plast and Comp 25:1279
70. Tanyildizi H (2009) Statistical analysis for mechanical properties of polypropylene fiber reinforced lightweight concrete containing silica fume exposed to high temperature. Mat and Desig 30:3252–3258
71. Fung CP, Huang CH, Doong JL (2003) The study on the optimization of injection molding process parameters with gray relational analysis. J of Reinf Plast and Comp 22:51
72. Patnaik A, Satapathy A, Mahapatra SS, Dash RR (2008) A Taguchi approach for investigation of erosion of glass fiber polyester composites. J of Reinf Plast and Comp 27:871
73. Patnaik A, Satapathy A, Mahapatra SS, Dash RR (2008) Implementation of Taguchi design for erosion of fiber-reinforced polyester composite systems with SiC filler. J of Reinf Plast and Comp 27:1093
74. Patnaik A, Satapathy A, Mahapatra SS, Dash RR (2008) Parametric optimization erosion wear of polyester-GF-alumina hybrid composites using the Taguchi method. J of Reinf Plast and Comp 27:1039
75. Patnaik A, Satapathy A, Mahapatra SS, Dash RR (2009) Modeling and prediction of erosion response of glass reinforced polyester-flyash composites. J of Reinf Plast and Comp 28:513
76. Pelegri AA, Tekkam A (2003) Optimization of Laminates' fracture toughness using design of experiments and response surface. J of Comp Mat 37:579
77. Fung CP (2003) Manufacturing process optimization for wear property of fiber-reinforced polybutylene terephthalate composites with grey relational analysis. Wear 254:298–306
78. Geng Y, Laborie MPG (2009) The impact of silane chemistry conditions on the properties of wood plastic composites with low density polyethylene and high wood content. Polym Comp 31(5):897–905
79. Jack DA, Smith DE (2008) Elastic properties of short-fiber polymer composites, derivation and demonstration of analytical forms for expectation and variance from orientation tensors. J Comp Mat 42(3):277–308
80. Jack DA, Smith DE (2007) The effect of fibre orientation closure approximations on mechanical property predictions. Composites, Part A 38(3):975–982
81. Chang SH, Hwang JR, Doong JL (2000) Manufacturing process optimization of short glass fiber reinforced polycarbonate composites in injection molding. J of Reinf Plast and Comp 19:301
82. Xian G, Pu HT, Yi XS, Pan Y (2006) Parametric optmisation of pin-assisted-melt impregnation of glass fiber/polypropylene by Taguchi method. J Comp Mat 40:2087
83. Jalili K, Abbasi F, Nasiri M, Ghasemi M, Haddadi E (2009) Preparation and characterization of expandable St/MMA copolymers produced by suspension polymerization. J Cell Plast 45:197