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Friction welding for the manufacturing of PA6 and ABS structures reinforced with Fe particles

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In the present work PA6 matrix reinforced with metal powder (Fe) has been joined by friction welding with ABS matrix reinforced with Fe powder for structural applications (like: joining of pavement sheets, assembly of pipe lines etc.). The melt flow index (MFI) of PA6+Fe powder was put approximately equivalent to MFI of ABS + Fe powder by varying the proportion of Fe powder in PA6 and ABS matrix. After fixing proportion of Fe powder in PA6 and ABS material, these materials were used for preparation of feed stock filament of fused deposition modelling filament (FDM) by screw extrusion process. Finally two FDM filaments of PA6+Fe powder and ABS + Fe powder were fed into FDM machine independently. The functional prototypes of circular cross-section were prepared on FDM machine (one with filament of PA6+ Fe powder and second with ABS + Fe powder). These geometrical shapes of two dissimilar plastic/polymer materials were used on friction welding setup. Finally under best parametric conditions of feed, rpm etc. these reinforced polymer materials were successfully joined. This study provides a response surface methodology (RSM) based statistical model for enhancing the weldability of dissimilar polymer materials (as an alternative method) with improved mechanical/metallurgical properties.

1. Introduction

Friction welding is also known as solid state process that joins similar and dissimilar metallic or polymeric based materials. This is considered originally a conventional forming process that has a history as far back as the "Bronze age", when gold coins and complex structures were formed through application of pressure welding. One of the great evidence of this technique can be seen as "Iron pillar" at Delhi India, which was made around 1700 year ago. The friction welding as professional techniques has emerged in the beginning of 20th century [1]. Along with friction welding, there are other solid state welding techniques capable for joining of dissimilar plastic based material. One of the solid state welding processes, known as ultrasonic welding which is best applicable as "ease of automation" among all its kind [2]. But this process cannot be considered as economical process for field application as compared to the friction welding. Microwave welding is assumed to be the best applicable technique for joining of inherently conducting polymers [3], but most of the polymers are considered as non-conducting in nature so application of microwave welding is very limited. The researchers in the field of solid state welding of amorphous polymers have introduced a term called "healing" which has been explained as when two same amorphous polymers contacted to each other at temperature greater than their glass transition temperature, resulted into formation of bond layer, it is known as healing [4]. The another process named CO_2 laser welding emerged as a newer solid state welding technique which has the capability to weld the non-conducting polymers [5], but this laser welding concept is not a cost effective process anymore. The variety of finite element modeling and numerical modeling for solid state welding of polymer welding has been developed by the researchers. A dynamic Monte-Carlo lattice model has been developed for simulation of polymer chain at welded face undergone to welding process [6]. The amorphous thermoplastic like: polyetherimide (PEI), which natured as high melting point polymer can be joined with hot tool welding [7]. Similar to dynamic Monte Carlo lattice model, another simulation model has been developed

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Abbreviations

ABS	Acrylonitrile butadiene styrene
DSC	Differential scanning calorimeter
MFI	Melt flow index
PA6	Polyamide 6
RSM	Response surface methodology

by the researcher called "Meso scale model" for welding of polymers [8]. The another solid state welding variant known as vibration welding, is used for joining of complex structure parts fabricated from injection molding [9]. Under the categories of solid state welding processes, the resistance welding has emerged as a solid state welding process that has great potential for high performance application of fiber reinforced thermoplastic composites welding [10]. The reinforcement of metallic or nonmetallic fillers like Fe, Al, Cu, glass fiber, carbon fiber always lead to contribution of better mechanical or metallurgical properties. The researchers have observed the formation of a hybrid layer in between the welded interface which contributed to the better mechanical properties, by resistance welding of carbon fiber reinforced PEI [11]. Other than thermoplastic materials, electrical resistance welding can be best applicable for the welding of thermo-set materials [12]. Unlike fusion bonding, auto-adhesion is a variant of solid state welding technique that is used for the welding/joining of polymeric materials [13]. Friction welding technique was originally come into existence for joining similar metallic pieces only [14]. But later on much research has been carried towards feasibility of friction welding for dissimilar metals like; steel-aluminum and steel-copper and aluminum-magnesium cylindrical piece joining [15,16]. The researcher in present era aims for welding of dissimilar polymers. Some studies have been reported the mechanism of friction welding for dissimilar polymeric material like; ABS and high density polyethylene (HDPE) [17]. The investigations for mechanical, thermal, and metallurgical properties for frictionally welded joints have been made [18–20]. Fusion, bonding, deformation and microstructure at welded interface have been investigated by the scanning electron microscope (SEM) to check the effects of input process [16,21,22]. The study outlined that joining of similar polymer (ABS/Nylon6 etc.) to itself is very much feasible. Along with this joining of dissimilar polymers (like ABS to HDPE) is also feasible. The effect of using threaded pin for friction stir welding of Nylon6 plates has improved mechanical mixing at the joint interface [23]. The researcher have developed different techniques of solid state welding and its variant. But there is a limitation of joint strength (for friction welded joints) of these thermoplastics that hinders its use in different engineering applications. Friction welding has emerged as repair and maintenance tool, where two oil or gas pipeline can be joined together by using a friction welding variant called "Friex" [24]. Friction inertia welding concept is widely accepted in aerospace applications [25]- [26]. Reinforcement of nano-composite or metal powder in thermoplastic matric leads to better joining efficiency with friction welding. The studies have been conducted to check the improvement in joint strength with use of SiO_2 nano-composite in welding of poly (methyl-methacrylate) PMMA. The welding of PMMA-SiO_2 was observed to be possible with better mechanical strength [27]. It has been established that the reinforcement of nano-composite (carbon nanotube, grapheme and nano sized metal powder) with polymers is responsible for the improved mechanical and metallurgical properties [28–32].

The literature review reveals that lot of work has been reported for friction welding of metals, non-metals or thermoplastic for different areas of applications [33–39]. But hitherto, very less has been reported for friction welding of dissimilar polymers like; PA6 and ABS. This work is an extension of work performed by Singh et al. [39] (especially as regards to thermal characterization and statistical modelling). In the present work attempts have been made to perform friction welding for FDM printed dissimilar thermoplastic (ABS and PA6) by reinforcement of Fe metals powder with preview of rheology and compatibility in terms of thermal and mechanical properties.

2. Experimental

2.1. Materials

PA6 is an engineering thermoplastic material that has extensive application in different areas like; automobile, construction and repairs (Civil engineering), aerospace and used as rapid tooling in medical field. PA6 has good material characteristics like; wear or erosion resistivity, thermal, chemical and dimensional stability, excellent elongation properties and etc. Acrylonitrile linked to long carbon chain of ABS contributes as high strength, whereas butadiene and styrene enhance the molding and additive manufacturing capability. ABS has good impact and toughness properties. ABS is amorphous in nature and has no true melting point but has a melting range. Table 1 shows the relative comparison of ABS and PA6 based upon different mechanical, thermal and chemical properties.

2.2. MFI analysis

MFI is a consideration of material characteristics and it determines the rheological behavior of polymers [40]. Various studies have been contributed to establish the relationship between MFI, mechanical and thermal properties [41–46]. Most of the polymers are investigated for their MFI (g/10min) as per ASTM D1238 standard (at temperature of 230 °C and applied mass of 3.8 Kg). Fig. 1 shows the experimental setup for MFI investigation. Table 2 shows the MFI of ABS and PA6 with different proportion of Fe

Table 1
Mechanical, chemical and thermal properties of ABS and PA6 [33-37].

Properties	ABS	PA6
Tensile strength (kgf/mm^2)	3.516–5.274	4.219–16.878
Flexural strength (kgf/mm^2)	189.881–267.240	274.272–773.590
Chemical resistance	Poor to fair	Good to excellent
Glass transition temperature (°C)	105	46
Melting point (°C)	No true melting(amorphous)	215 °C
Chemical formula	$(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$	$(C_6H_{11}NO)_n$
Density (g/cm^3)	0.9–1.53	1.084
Specific heat capacity (J/kg.K)	1300	1600