Design a Constitutive Fuzzy Logic Model of Warpage on Shape Memory Polyurethane Parts

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***Abstract*— Injection moulding process of shape memory thermoplastic polymers is important for manufacturing of stimuli-responsive plastic parts in mass production. Moulding conditions have remarkable role on the controlling of permanent shape of moulded parts. Warpage is the one of the main factors, which define the part shape quality. A limited number of experimental studies have been conducted to determine the relationship between warpage and moulding parameters. According to the experimental study, injection pressure and cooling time are the most effective parameters on warpage. But, it is very difficult to define an accurate mathematical model that gives the warpage value with respect to injection pressure and cooling time. In this study, the relationship between moulding parameters and warpage was defined as a constitutive model by using fuzzy logic. Fuzzy model consists of two input variables and one output variable. Cooling time and injection pressure were selected as input variables and warpage was selected as output variable for the fuzzy model. The results showed that the model represented experimental results with high confidence.**

***Keywords*— Permanent shape, Warpage, Shape memory polymers, Fuzzy logic**

I. INTRODUCTION

Shape memory effect (SME) makes materials usable in various part shapes and doing a work while shape changing when materials facing stimuli such as temperature, pH, light, electric current, magnetic field etc. [1-3]. As having SME property, shape memory polymers (SMPs) provide two or more working shapes in one part as different from general-purpose polymer materials.

Although SMPs, which are, but not limited to, shape memory polyurethane (SMPU), polystyrene shape memory polymer (PSMP), biodegradable SMPs based on PVA poly(vinyl alcohol), PLA polylactide and PEG poly(ethylene glycol), have only been discovered recently [4]. SMPs have greatly enhanced and raised their industrial applications and capabilities such as; wires ([4], [5], [6], [7]) stents ([8], [9], [10]), bio degradable stent [11], coil [12], Braille paper, self-assembly/disassembly screws [13], self-open hole, fasteners and snap-fit design for self-disassembly ([13], [14], [15], [16], [17]), winglet, hinges, booms, antennas, optical mirrors for space cars ([6], [18], [19]).

SMPU has advantages for example; the different switching temperature (Tg) could be set by controlling synthesis process or remoulding because of its thermoplastic property. Designing and production of new SMP parts are new focusing points for researchers and engineers. For instance, in Figure 1, a temperature sensitive thermoplastic shape memory part, which has one-way shape memory effect, has two stages for processing before become a real part. First stage is moulding and second is called programming. In the moulding stage, the part is moulded as a normal thermoplastic part and after that in the second stage the part is heated to material`s Tg (glass transition temperature) and having form of its new shape. While keeping its in new shape, the part cooled down under the Tg.

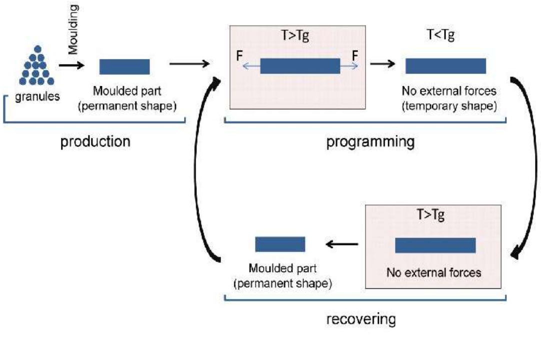

Fig. 1 One-way shape memory effect of a temperature responsive shape memory polymer

Although they are new generation features or systems, their manufacturing or forming process as a part starts by traditional methods such as injection moulding, extrusion, compression moulding and so on. At present, the injection moulding is the most common method for producing plastic parts. It is well known that the moulding methods have significant influence on moulded parts. Many studies show that injection moulding process has effects on mechanical and physical properties of moulded plastic parts for instance; dimensional accuracy, shrinkage, warpage, tensile strength, impact strength or residual stress ([20], [21], [22], [23], [24], [25])

According to previous studies, the effects of moulding parameters could be summarised shortly as (i) at longer cooling time, warpage ([26], [27]) and tensile residual stresses [28] reduces, (ii)cooling time is the most influential factor on generation of residual stress in plastics ([29], [30], [31], [32], [33], [34]), (iii)while increasing injection pressure, residual stresses rise up [35].

Warpage on injection moulded high-density polyethylene (HDPE) box shaped specimen is in proportional relation to melt temperature and in inverse relation to cooling time [thesis 106]. In injection moulded polycarbonate/acrylonitrile butadiene styrene (PC/ABS) specimen, warpage reduces by rising melt temperature ([23], [22], [36]). Gao and Wang reported that during moulding at low melt temperature, flow based residual stresses generate during filling and then caused warpage because at low melt temperature the molten plastics has not good flow ability [22]. Another study reported by Chiang says that mould temperature is the most influential parameter on the properties of a cell phone cover moulded with PC/ABS especially for reducing shrinkage and warpage [36]. Warpage decreased by increasing mould temperature in PP rectangular flat shape parts [28]. About packing pressure, warpage is lower at low packing pressures in HDPE flat parts [28]. Gao and Wang mentioned that high packing pressure persuades high stresses thus high warpage on PC/ABS parts. In addition, high packing pressure makes changes on the stress distribution of the parts especially the gate region, and around of the gate region and makes warpage rise up [22]. In another study, Huang and Tai found that warpage rises when packing pressure increases [23]. On the other hand, when high packing pressure was applied on polystyrene (PS) parts, warpage decreased [35]. At the packing stage of the injection moulding, another important parameter is packing time. The effect of packing pressure could be considered together with packing pressure and cooling time because the cooling of molten plastics also already starts when injection stage starts in the mould with standard sprue, and runner system.

There are some examples of fuzzy logic application in injection moulding process. Tsoi and Gao (1999) estimated a model based on Fuzzy Logic to control the injection velocity for thermoplastics injection moulding using a rule-based controller. They reported that Fuzzy based model has better performance than the conventional proportional-integral-derivative (PID) controller [37]. Salimi et al. (2013) predicted injection moulding flow length of engineering plastics for melt temperature and injection pressure by a fuzzy logic model [38].

The short summary of literature shows that the injection moulding parameters have effects on warpage of plastics. In addition, the effects and its way could be changing for different plastics because of the molecular differences. In this study, a fuzzy logic model was constituted to predict warpage on injection moulded SMPU parts. The model has two inputs and one output called warpage. Two inputs as injection moulding parameters namely cooling time and injection pressure were chosen depending on experimental study, which is previously carried out [39].

II. METHODS

In the experimental section of the study, six moulding parameters were examined by Taguchi's L27 orthogonal design table [39]. According to the experimental study, injection pressure and cooling time are the most effective parameters on warpage of SMPU samples. In Table 1, the input parameters and their levels of the model were given. But, it is very difficult to define an accurate mathematical model that gives the warpage value with respect to injection pressure and cooling time.

In this study, the relationship between moulding parameters and warpage was defined as a constitutive model by using fuzzy logic. Fuzzy model consists of two input variables and one output variable. Cooling time and injection pressure were selected as input variables and warpage was selected as output variable for the fuzzy model. Block diagram of the fuzzy model is shown in Figure 2.

TABLE I
INPUT PARAMETERS AND LEVELS

Factors	**Levels**		
Cooling time (s)	15	22.5	30
Injection pressure (Bar)	500	600	700

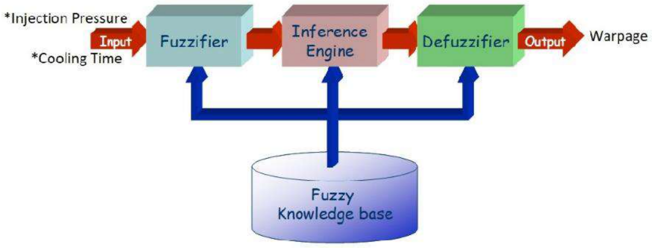

Fig. 2 Block diagram of proposed fuzzy model

To estimate the warpage (W) in the proposed model by using fuzzy set theory, the cooling time (tc) and the injection pressure (P) are employed. The fuzzy warpage estimator is designed to process fuzzy quantities only. Therefore the crisp input values of cooling time (tc) and injection pressure (P) must be converted to fuzzy sets before being used. This process is called fuzzification operation. Fuzzy input variables are tc (cooling time) and P (injection pressure). Fuzzy output variable is W (warpage). It has chosen three linguistic levels for cooling time, three linguistic levels for injection pressure and 9 linguistic levels for warpage. The membership functions of the fuzzy variables (cooling time, injection pressure and warpage) are shown in Figure 3.

The warpage is determined by using fired if-then rules of the fuzzy logic estimator. The rules take the form ‘ If tc is T1 and

P is P1 then W is W1'. The rule table is shown in Table 2. The fuzzy output is computed by using MAX-MIN composition method. Then crisp output of the estimator, which is the actual warpage, is determined by centroid defuzzification method.

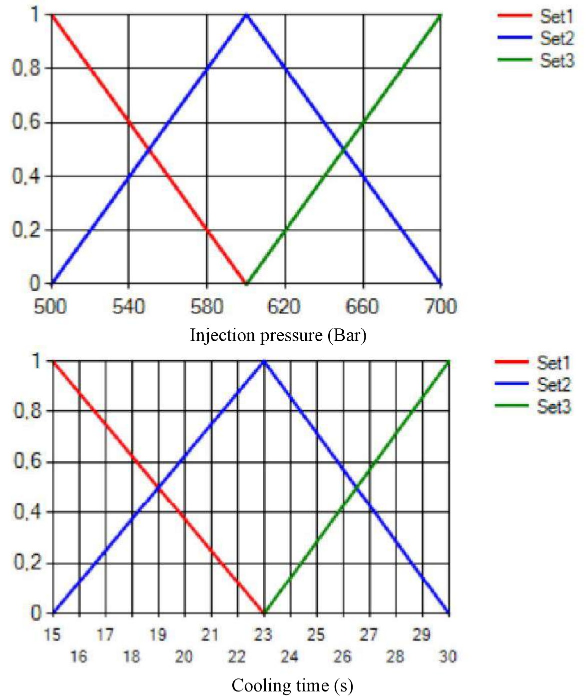

Fig. 3 Membership functions of the input variables including injection pressure and cooling time

The steps for warpage estimation in the proposed model are summarized as follows:

1. Sample the values of cooling time (tc) and the injection pressure (P).
2. Determine the fuzzy sets and membership functions for cooling time and injection pressure.
3. Determine the warpage (W) according to the each fired individual fuzzy rule.
4. Calculate the crisp warpage by using centroid defuzzification operation.
5. Go to step 1

III. RESULTS

To explore the effectiveness of the proposed modelling, comparison of the results obtained from fuzzy based modelling and experimental data has been made. Figure 4 shows a sum of experimental results that descripting the effects of injection pressure and cooling time on warpage. Predicted amounts of warpage in SMPU samples by the fuzzy logic model depending on injection pressure and cooling time are given in Figure 5. In the figure, minimum warpage values were generated at low-level injection pressure (500 Bar) and high level (30 s) cooling time as parallel with the experimental results. In addition, at high-level (700 Bar) injection pressure and low-level (15 s) cooling time, the warpage has maximum values.

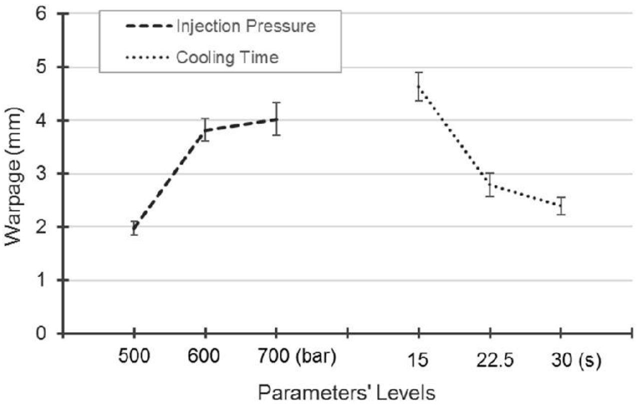

Fig. 4 Experimental main effect plots of warpage [39]

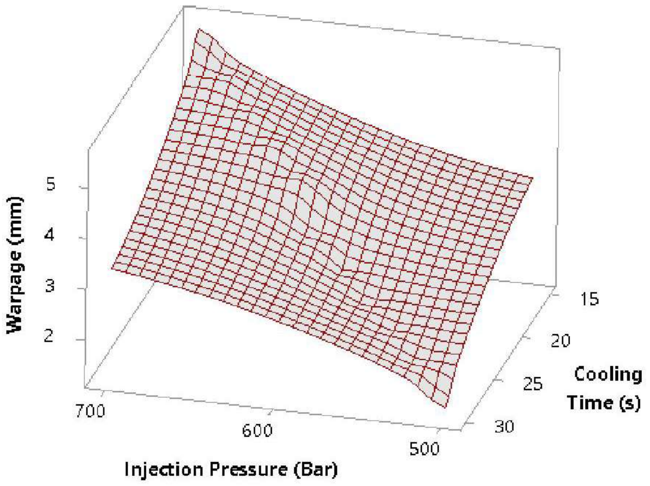

Fig. 5 Predicted amounts of warpage by the fuzzy logic model in relation to injection pressure and cooling time

Figure 6 shows that warpage and cooling time changes according to different injection pressure. In similar, the graph of warpage, and injection pressure were given in Figure 7. Those graphs make clear the relationship among warpage, cooling time and injection pressure.

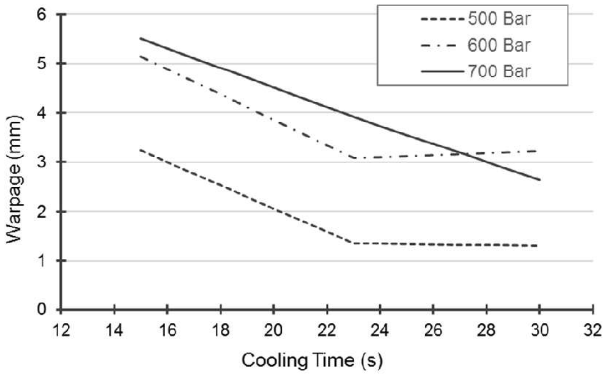

Fig. 6 Warpage versus cooling time by injection pressure

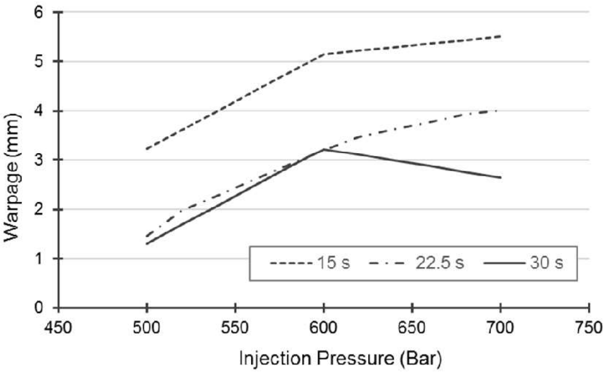

Fig. 7 Warpage versus injection pressure by cooling time

During moulding of the SMPU materials, 500 Bar injection pressure seems better injection pressure to get lower warpage. Middle-level or high-level cooling times have similar effect at lower injection pressure. If high-level injection pressure must be choosing, high level or longer cooling time should be picking up to make warpage decreases.

IV. CONCLUSIONS

In this study, a fuzzy logic model was constituted for prediction of warpage on injection moulded SMPU parts. The results showed that the model represented experimental results with high confidence and the model could be using to choose correct injection pressure and cooling time combination for moulding SMPU parts with lower warpage.

REFERENCES

[1] S. Hayashi, *Properties and applications of polyurethane series shape memory polymer*. Amsterdam: Elsevier Science B.V., 1993.

[2] A. Lendlein and S. Kelch, "Shape-Memory Polymers," *Angewandte Chemie International Edition,* vol. 41, pp. 2034-2057, 2002.

[3] M. Behl and A. Lendlein, "Shape-memory polymers," *Materials Today,* vol. 10, pp. 20-28, 2007.

[4] L. Sun, W. M. Huang, Z. Ding, Y. Zhao, C. C. Wang, H. Purnawali, *et al.*, "Stimulus-responsive shape memory materials: A review," *Materials and Design,* vol. 33, pp. 577–640, 2012.

[5] B. Y. W.M. Huang, Yong Qing Fu, *Polyurethane Shape Memory Polymers*, 1st Edition ed. Boca Raton: CRC Press, 2011.

[6] J. Leng, Xin Lan, Yanju Liu, and S. Du, "Shape-memory polymers and their composites: Stimulus methods and applications," *Progress in Materials Science,* vol. 56, pp. 1077–1135, 2011.

[7] W. Small IV, T. S. Wilson, W. J. Benett, J. M. Loge, and D. J. Maitland, "Laser-activated shape memory polymer intravascular thrombectomy device," *Optics Express,* vol. 13, pp. 8204-8213, 2005/10/03 2005.

[8] M.-C. Chen, Y. Chang, C.-T. Liu, W.-Y. Lai, S.-F. Peng, Y.-W. Hung, *et al.*, "The characteristics and in vivo suppression of neointimal formation with sirolimus-eluting polymeric stents," *Biomaterials,* vol. 30, pp. 79-88, 2009/01/01/ 2009.

[9] C. Wischke and A. Lendlein, "Shape-Memory Polymers as Drug Carriers—A Multifunctional System," *Pharmaceutical Research,* vol. 27, pp. 527-529, 2010.

[10] H. M. Wache, D. J. Tartakowska, A. Hentrich, and M. H. Wagner, "Development of polymer stent with shape meory effect as a drug delivery system," *Journal of Material Science: Materials in Medicine* vol. 14, pp. 109-112, 2003.

[11] Barry O'Brien and W. Carroll, "The evolution of cardiovascular stent materials and surfaces in response to clinical drivers: A review," *Acta Biomaterialia,* vol. 5, pp. 945–958, 2009.

[12] S. Tang, C.-Y. Zhang, M.-N. Huang, Y.-F. Luo, and Z.-Q. Liang, "Fallopian tube occlusion with a shape memory polymer device: evaluation in a rabbit model," *Contraception,* vol. 87, pp. 235–241, 2013.

[13] J. D. Chiodo, N. Jones, E. H. Billett, and D. J. Harrison, "Shape memory alloy actuators for active disassembly using 'smart' materials of consumer electronic products," *Materials and Design,* vol. 23, pp. 471–478, 2002.

[14] J. Carrell, D. Tate, S. Wang, and H.-C. Zhang, "Shape memory polymer snap-fits for active disassembly," *Journal of Cleaner Production,* vol. 19, pp. 2066-2074, 2011.

[15] B. He, H. Li, and K. Jin, "Shape memory polymer actuated hollow snap-fit design analysis," *Materials and Design,* vol. 47, pp. 539–550, 2013.

[16] H. Li, K. Jin, B. He, and Y. Chen, "Hollow structure snap-fit design embedded with shape memory polymer sheet," *CIRP Annals - Manufacturing Technology* vol. 61, pp. 31–34, 2012.

[17] H.-C. Zhang, J. Carrell, S. Wang, D. Tate, and S. Imam, "Investigation of a multiple trigger active disassembly element," *CIRP Annals - Manufacturing Technology,* vol. 61, pp. 27–30, 2012.

[18] A. Metcalfe, A.-C. Desfaits, I. Salazkin, L. H. Yahia, W. M. Sokolowski, and J. Raymond, "Cold hibernated elastic memory foams for endovascular interventions," *Biomaterials,* vol. 24, pp. 491-497, 2003/02/01/ 2003.

[19] X. Lan, J. S. Leng, and S. Y. Du, "Design of a Deployable Antenna Actuated by Shape Memory Alloy Hinge," *Materials Science Forum,* vol. 546-549, pp. 1567-1570, 2007.

[20] T. V. Zhil'tsova, M. S. A. Oliveira, and J. A. F. Ferreira, "Relative influence of injection molding processing conditions on HDPE acetabular cups dimensional stability," *Journal of Materials Processing Technology,* vol. 209, pp. 3894–3904, 2009.

[21] Jansen and G. Titomanlio, "Effect of pressure history on shrinkage and residual stresses—injection molding with con-strained shrinkage," *Polymer Engineering and Science,* vol. 36, pp. 2029–2040, 1996.

[22] Y. Gao and X. Wang, "Surrogate-based process optimization for reducing warpage in injection molding," *Journal of Materials Processing Technology,* vol. 209, pp. 1302–1309, 2009.

[23] M.-C. Huang and C.-C. Tai, "The effective factors in the warpage problem of an injection-molded part with a thin shell feature," *Journal of Materials Processing Technology,* vol. 110, pp. 1-9, 2001/03/01/ 2001.

[24] K. K. Kabanemi, H. Vaillancourt, H. Wang, and G. Salloum, "Residual Stresses, Shrinkage, and Warpage of Complex Injection Molded Products: Numerical Simulation and Experimental Validation," *Polymer Engineering and Science,* vol. 38, pp. 21-37, 1998.

[25] B. Ozcelik and T. Erzurumlu, "Comparison of the warpage optimization in the plastic injection molding using ANOVA, neural network model and genetic algorithm," *Journal of Materials Processing Technology,* vol. 171, pp. 437-445, Feb 2006.

[26] X. Wang, G. Zhao, and G. Wang, "Research on the reduction of sink mark and warpage of the moulded part in rapid heat cycle moulding process," *Materials and Design,* vol. 47, pp. 779–792, 2013.

[27] R. Sánchez, J. Aisa, A. Martinez, and D. Mercado, "On the relationship between cooling setup and warpage in injection molding," *Measurement,* vol. 45, pp. 1051–1056, 2012.

[28] Ş. Katmer and Ç. Karataş, "Effects of Injection Molding Conditions on Residual Stress in HDPE and PP Parts," *Journal of the Faculty of Engineering and Architecture of Gazi University,* vol. 30, pp. 319-327, 2015.

[29] T. Glomsaker, A. Larsen, and E. Andreassen, "Experimental and numerical investigation of warpage of semicrystalline polymers in rotational molding," *Polymer Engineering and Science,* vol. 45, pp. 945–952, 2005.

[30] E. Q. Clutton and J. G. Williams, "On the measurement of residual stress in plastic pipes," *Polymer Engineering and Science,* vol. 35, pp. 1381–1386, 1995.

[31] H. Hassan, N. Regnier, C. Le Bot, and G. Defaye, "3D study of cooling system effect on the heat transfer during polymer injection molding," *International Journal of Thermal Sciences,* vol. 49, pp. 161-169, 2010.

[32] H. Hassan, N. Regnier, C. Pujos, E. Arquis, and G. Defaye, "Modeling the effect of cooling system on the shrinkage and temperature of the polymer by injection molding," *Applied Thermal Engineering,* vol. 30, pp. 1547–1557, 2010.

[33] S. H. Tang, Y. J. Tan, S. M. Sapuan, S. Sulaiman, N. Ismail, and R. Samin, "The use of Taguchi method in the design of plastic injection mould for reducing warpage," *Journal of Materials Processing Technology,* vol. 182, pp. 418-426, Feb 2007.

[34] H. Qiao, " A systematic computer-aided approach to cooling system optimal design in plastic injection molding," *International Journal of Mechanical Sciences,* vol. 48, pp. 430-439, 2006.

[35] S. Katmer and C. Karatas, "The Effects of Molding Conditions on The Residual Stresses in Injection Molded Polystyrene Flat Parts," *Journal of the Faculty of Engineering and Architecture of Gazi University,* vol. 27, pp. 501-507, 2012.

[36] K.-T. Chiang, "The optimal process conditions of an injection-molded thermoplastic part with a thin shell feature using grey-fuzzy logic: A case study on machining the PC/ABS cell phone shell," *Materials and Design,* vol. 28, pp. 1851–1860, 2007.

[37] H.-P. Tsoi and F. Gao, "Control of injection velocity using a fuzzy logic rule-based controller for thermoplastics injection molding," *Polymer Engineering & Science,* vol. 39, pp. 3-17, 1999.

[38] A. Salimi, M. Subaşı, L. Buldu, and Ç. Karataş, "Prediction of flow length in injection molding for engineering plastics by fuzzy logic under different processing conditions," *Iranian Polymer Journal,* vol. 22, pp. 33-41, January 01 2013.

[39] S. Katmer, "Investigation of Effects of Injection Moulding Parameters on Shape Memory Polyurethane," PhD, Graduate School of Natural and Applied Sciences, Gazi University, Ankara, 2017.